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Series Editor: Peijian Ye

Jindong Li

Satellite Remote Sensing Technologies

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Series Editor

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Jindong Li

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Jindong Li
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Series Editor's Preface

China's space technology and science research have earned a place in the world, but have not been compiled into a series of systematic publications yet. In 2018, the series *Space Science and Technology* edited mainly by me and co-authored by the leading figures in China's space industry was published in China, when China Academy of Space Technology was celebrating the 50th anniversary of its founding. This collection contains 23 volumes in Chinese, only 10 of which have been selected, re-created, and translated into English. In addition, each English volume has been re-created at the suggestion of the Springer, by deleting the contents similar to Springer's existing publications and adding the contents that are internationally advanced and even leading, and bear both Chinese characteristics and worldwide universality. This series fully reflects the knowledge and engineering experience recently accumulated by Chinese scientists and engineers in space technology and science research.

As the Editor-in-Chief of this series, I always insist that this collection must be of high quality, either in the Chinese version or English version. First, the contents of this series must be condensed and sublimated based on the combination of theory and practice, so as to provide both a theoretical value and engineering guidance. Second, the relationships between past knowledge and state of the art and between other people's work and our own new findings should be properly balanced in the book contents to ensure the knowledge systematicness and continuity and to highlight new achievements and insights. Each volume intends to introduce the readers something new. Third, the English version should be customized for international exposure and play a solid supporting role for China to contribute to the world's space field.

This collection consists of 10 volumes, including *Spacecraft Thermal Control Technologies*, *Spacecraft Power System Technologies*, *Spacecraft Electromagnetic Compatibility Technologies*, *Technologies for Spacecraft Antennas Engineering Design*, *Satellite Navigation Systems and Technologies*, *Satellite Remote Sensing Technologies*, *Spacecraft Autonomous Navigation Technologies Based on Multi-source Information Fusion*, *Technologies for Deep Space Exploration*, *Space Robotics*, *Manned Spacecraft Technologies*.

Satellite Remote Sensing Technologies reflects the latest achievements made in the development of Chinese satellite remote sensing technology. It has been summarized, sublimated, and refined from practice by frontline engineers. This volume describes the basic theory of satellite remote sensing technology systematically and comprehensively, and covers the design, engineering implementation methods, and practical application examples of remote sensing satellites.

The publication of this series adds a new member to the international family of space technology and science publications, and intends to play an important role in promoting academic exchanges and space business cooperation. It provides comprehensive, authentic, and rich information for international space scientists and engineers, enterprises, and institutions as well as government sectors to have a deeper understanding of China's space industry. Of course, I believe that this series will also be of great reference value to the researchers, engineers, graduate students, and university students in the related fields.

Peijian Ye
Academician
Chinese Academy of Sciences
Beijing, China

Preface

Based on the overall design of the spaceborne remote sensing system, this book concisely summarizes China's experience in the spaceborne remote sensing system technology and its engineering application.

Since the launch of a major science and technology project on high-resolution Earth observation system, China has made remarkable achievements in satellite remote sensing technology and major breakthroughs in the overall design and high-precision control of visible, infrared, hyperspectral, and microwave remote sensing satellites and in the processing and transmission of high-speed image data. China has launched the high-resolution remote sensing satellites such as Gaofen-1, Gaofen-2, Gaofen-3, Gaofen-4, Gaofen-8, and Gaofen-9 in succession. These satellites have played an important role in the monitoring of land and resources, the exploitation of mineral resources, the fine management of cities, the monitoring of traffic facilities, the survey of agricultural and forestry resources, and the recovery and reconstruction of disaster-hit areas, while enabling China's satellite remote sensing technology to achieve leapfrog development. Based on the overall design and flight verification of the above satellites, this book summarizes the state of the art of satellite remote sensing technology.

The focus of this book is the mission analysis and overall design of remote sensing satellite system. Through the mission analysis and design, the mission objectives and requirements (mission and tasks, functions and performance, etc.) proposed by the users are transformed into the overall design requirements and constraints on remote sensing satellite system, such as those on satellite orbit, load configuration and system composition. Meanwhile, the selection of carrier rocket and launch site is also discussed. Finally, the development trend of spaceborne remote sensing system in the future is presented by combing the future development trend of spaceborne remote sensing technology.

This book consists of 10 chapters. In Chap. 1, the basic knowledge on the general composition of satellite remote sensing system engineering, the physical basis of satellite remote sensing, the near-Earth space environment and its effects are introduced. In Chap. 2, the mission characteristics of remote sensing satellite and its orbit design method are addressed. In Chap. 3, the overall design methods of

visible panchromatic/multispectral remote sensing satellite systems are presented. In Chaps. 4 and 5, the overall design methods of infrared/hyperspectral remote sensing satellite systems are described, respectively. In Chap. 6, the overall design method of high-precision survey satellite system is given. In Chap. 7, the overall design method of synthetic aperture radar (SAR) remote sensing satellite system is elaborated on. In Chap. 8, the overall design method of microwave remote sensing satellite system is discussed. In Chap. 9, the overall design method of geosynchronous optical remote sensing satellite system is introduced. In Chap. 10, the future development trend of satellite remote sensing technology is given.

This book is mainly edited by Jindong Li and compiled and proofread by Jindong Li, Ting Li, Xiang Li, and Hezhi Sun. Chapter 1 was written by Chen Ni, Zhiping Zhang, and Jindong Li; Chap. 2 by Meili Huang, Qiao Zhao, and Hao Feng; Chap. 3 by Ting Li, Zhen Li, and Jindong Li; Chap. 4 by Chen Ni and Jindong Li; Chap. 5 by Zhen Li, Lei Yao, and Jindong Li; Chap. 6 by Xinwei Zhang; Chap. 7 by Zheng Lv; Chap. 8 by Mingming Xu; Chap. 9 by Xianghao Kong; and Chap. 10 by Dong Yang.

The compilation of this book took more than 2 years and received careful guidance and great support from the experts such as Academician of Chinese Academy of Engineering Peijian Ye, President of the China Academy of Space Technology (CAST) Hongtai Zhang, and Director of the Science and Technology Commission of the CAST General Division Yongfu Wang. This book was also checked by Shiping Chen, Jijun Chang, Xiulai Hao, Shijun Ma, Wei Cai, Guojing Han, Guo Li, Zhenbo Cai, Tao Jin, Hong Jia, Yan Li, Jing Cao, Haitao Tang, Lei Yu et al, who put forward a lot of valuable suggestions during examination. The engineers from CAST General Division Xiaoheng Liang and Xiujuan Liang, together with the Springer editors, have done a lot of work on the publication of this book. Here, the authors would like to express sincere thanks to them.

Beijing, China

Jindong Li

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About the Author



Prof. Dr. Jindong Li, doctoral supervisor and expert in the field of aerospace remote sensing, currently works in Beijing Institute of Spacecraft System Engineering in China Academy of Space Technology as a chief designer in a certain area. Professor Li mainly engaged in the overall design of remote sensing satellites and research on spacecraft thermal control technology, and has successively served as the chief designer of several remote sensing satellites, a project expert in Major Basic Research on National Security, the chief scientist for National Defense 973 Program, and a member of Russian Academy of Cosmonautics by K. E. Tsiolkovsky. He has won 3 second prizes of the National Science and Technology Progress Award, 4 first prizes, 1 second prize, and 2 third prizes of the National Defense Science and Technology Award, and has published more than 80 academic papers in domestic and foreign journals and important academic conferences.

Chapter 1

Fundamentals of Satellite Remote Sensing Technology



1.1 Introduction

The history of remote sensing satellites in China dates back to the 1970s. The remote sensing satellite has been developed from recoverable satellites to transmission satellites with different spectrum segments, such as visible light, infrared, hyperspectral, and microwave bands. During the development, key technologies such as high-resolution large-scale optical system, Synthetic Aperture Radar (SAR) payload, hyperspectral imaging, high-precision dynamic imaging, and high-orbit imaging have been conquered and a series of four major operational satellites for resources, meteorology, oceans, and environment disaster relief have been established. At present, China's satellite remote sensing data have provided big data service support for industries such as national land and mineral resources management and monitoring, traffic network safety monitoring, geological hazard early warning, air and water environmental pollution monitoring, agricultural and forestry growth, pest monitoring and yield assessment, flood and waterlogging disaster monitoring, hydraulic facilities safety monitoring, as well as Earthquake disaster monitoring. Satellites FY series, and HY series have become one of the international meteorological and ocean satellite data sources.

In 2010, China launched a major scientific and technological project of high-resolution Earth observation system, and a global coverage, all-weather and full-spectrum "sky-eye network" will be built in 2020. By then, the spatial resolution of visible light and SAR of China's Earth observation satellites will be higher than 0.5 m, the spectral resolution will reach 3–5 nm, and the mapping accuracy will be better than the mapping indicator of 1:10,000, and the satellites will have fast attitude maneuverability. Currently, GF-1, GF-2, GF-3, GF-4, GF-8, GF-9 have been launched, among which, GF-3 and GF-4 are, respectively, high-resolution SAR imaging satellite and high-resolution geostationary orbit optical Earth observation satellite. These high-resolution satellites play an important role in the monitoring

of land resources, mineral resources development, urban refinement management, transportation facilities monitoring, forestry resources survey, disaster recovery, and reconstruction, so that the satellite remote sensing technology in China has achieved leapfrog development.

1.2 Physical Basis of Satellite Remote Sensing

1.2.1 *Electromagnetic Wave and Electromagnetic Spectrum*

1.2.1.1 Electromagnetic Wave

Remote sensing refers to a comprehensive technology of Earth observation that can collect, process, and finally image the electromagnetic wave information radiated and reflected by long-range targets using various sensing instruments without directly contacting objects to realize the detection and recognition of various objects on the ground. Any object has its unique electromagnetic wave reflection or radiation characteristics, and the information of electromagnetic wave reflected or emitted by the ground objects reaches the remote sensing sensor through the Earth's atmosphere. The sensor records the reflection intensity of the ground object to the electromagnetic wave and forms a remote sensing image. Therefore, remote sensing image is essentially a record of the interaction between electromagnetic radiation and the ground object. Electromagnetic wave and its basic characteristics are the basis of understanding the principle of remote sensing imaging.

Electromagnetic wave is a motion form of electromagnetic field. According to Maxwell's electromagnetic field theory, energy exists everywhere in space as long as there is a field. Any change in electric field can excite the magnetic field in its surrounding space, and any change in the magnetic field will induce the changing electric field around it. When this changing electromagnetic field propagates in space in the form of electromagnetic oscillation, the electromagnetic waves are formed. In fact, electromagnetic oscillation propagates in different directions. This transmission process of electromagnetic energy (including radiation, absorption, reflection, and transmission) is called electromagnetic radiation.

Electromagnetic wave is a transverse wave, which has a time and space periodicity. The time–space periodicity of the electromagnetic wave can be expressed by the wave function, as shown in Fig. 1.1.

The general functional expression for the electromagnetic wave with a single-wavelength is

$$\psi = A \sin[(\omega t - kx) + \varphi], \quad (1.1)$$

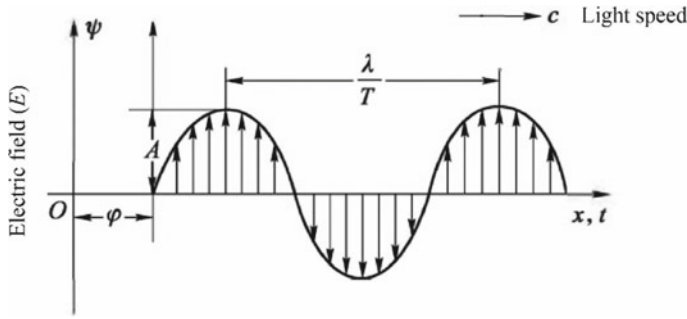


Fig. 1.1 Wave function diagram

where ψ is the wave function, indicating the electric field strength; A is the amplitude; ω is circular frequency, $\omega = 2\pi/T$; $k = 2\pi/\lambda$ is circular wave number; t represents time, x indicates the distance; and ϕ is the initial phase.

The wave function consists of amplitude and phase. In general, the sensor records only the amplitude information of the electromagnetic wave, ignoring the phase information. In the holography, in addition to recording the amplitude information of the electromagnetic wave, the phase information is also recorded.

1.2.1.2 Division of Electromagnetic Spectrum Band

Different electromagnetic waves have different wavelengths, frequencies, wave numbers or energies. The so-called electromagnetic spectrum is obtained by arranging the electromagnetic waves in the order of their wavelengths, frequencies, wave numbers, or energies. An example is shown in Fig. 1.2. Tables 1.1 and 1.2 are the division and naming of spectral bands and microwave frequencies from ultraviolet to infrared, respectively. If the electromagnetic waves are arranged in order of the increasing band frequency, they include radio wave, infrared (far-infrared, mid-infrared, near-infrared), Visible light, ultraviolet, X-ray, and gamma ray. The reason why the wavelengths of various electromagnetic waves are different is that the sources of electromagnetic waves are different. For example, radio wave is emitted by electromagnetic oscillation; microwave stimulated and transmitted by resonant cavity and waveguide tube is emitted into space by microwave antenna; infrared radiation is generated by energy-level transition of molecular vibration and rotation; visible light and near-ultraviolet radiation are generated by outer electron transition in atom and molecule; ultraviolet, X-ray, and gamma ray are produced by the transition of inner electrons and the change of state in the nucleus; and cosmic rays come from cosmic space.

Different types of electromagnetic waves have different properties due to different wavelength (or frequency). For example, visible light can be directly seen by the human eye in various colors, infrared rays can pass through the darkness in the

Fig. 1.2 Electromagnetic waves classified by wavelength

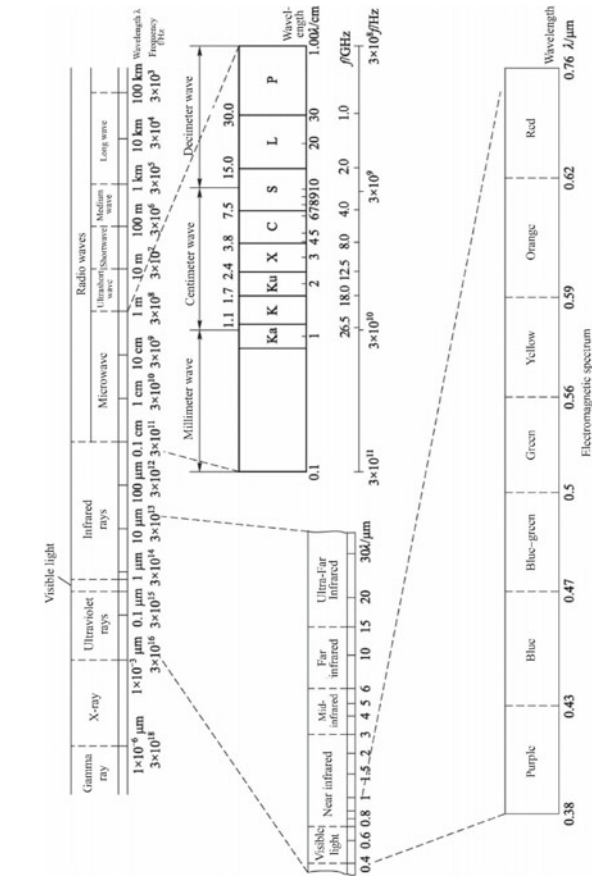


Table 1.1 Spectrum division from ultraviolet to infrared

Name	Abbreviation	Wavelength range
Ultraviolet	UV	10–400 nm
Ultraviolet-B	UV-B	280–320 nm
Visible light	V	400–700 nm
Near infrared	NIR	0.7–1.3 μm
Shortwave infrared	SWIR	1.3–3.5 μm
Thermal infrared	TIR	3.5–20 μm

night, and microwaves can penetrate obstacles, such as cloud, fog, smoke, and rain. However, they also have the commonality that all kinds of electromagnetic waves propagate at the same speed in vacuum (or air), equal to the speed of light: $c = 3 \times 10^8 \text{ m/s}$; and comply with the uniform law of reflection, refraction, interference, diffraction, and polarization; electromagnetic waves possess wave–particle duality,

Table 1.2 Microwave frequency partitioning and naming

Name	Frequency/GHz	Wavelength
p	0.2255–0.390	76.905–133 cm
L	0.3905–1.55	19.355–76.9 cm
S	1.555–4.20	7.145–19.35 cm
C	4.205–5.75	5.225–7.14 cm
X	5.755–10.9	2.755–5.22 cm
Ku	10.95–22.0	1.365–2.75 cm
Ka	22.05–36.0	8.335–13.6 mm
Q	36.05–46.0	6.525–8.33 mm
V	46.05–56.0	5.365–6.52 mm
w	56.05–100	3.005–5.36 mm

that is, electromagnetic waves can exhibit particle-like properties while particles can exhibit wave-like properties. In the process of electromagnetic radiation propagation, it is mainly shown as wave-like properties. The phenomena of interference, diffraction, polarization, and dispersion are all the manifestations of electromagnetic radiation wave-like properties. When electromagnetic radiation interacts with matter, it is mainly shown as particle-like properties. The wave and particle properties of electromagnetic waves vary with their wavelength, in general, the shorter the wavelength, the more obvious the particle properties radiated of electromagnetic waves; the longer the wavelength, the more obvious the wave properties radiated of electromagnetic waves. Taking full advantage of the two characteristics of wave–particle duality of electromagnetic wave, remote sensing technology can detect the electromagnetic radiation information carried by the object.

The electromagnetic waveband used in remote sensing technology mainly concentrates on the ultraviolet band to the microwave band. Visible light, infrared, and microwave bands are the most commonly used bands in remote sensing applications. Because of the different bands of electromagnetic waves applied by remote sensing, the characteristics of Earth observation are quite different.

(1) Visible spectrum band

The wavelength of visible light ranges from 0.38 to 0.76 μm . In the electromagnetic spectrum, visible light only occupies an extremely narrow band. Visible light is an electromagnetic wave that human vision can feel “bright”. When visible light enters the human eye, the subjective perception of the human eye in order of decreasing wavelength is red (0.62–0.76 μm), orange (0.59–0.62 μm), yellow (0.56–0.59 μm), green (0.50–0.56 μm), cyan (0.47–0.50 μm), blue (0.43–0.47 μm), and purple (0.38–0.43 μm).

The different objects reflection, transmission, scattering, and absorption of visible light have different characteristics. The human eye has the ability of continuous response to electromagnetic radiation in the visible band to sense the radiation

characteristics of different objects in the visible band and to distinguish different objects.

Visible light is the main band used by remote sensing technology to identify material characteristics. Visible light mainly comes from the earthly reflection of the sun's radiation. It can work only under the sunshine during the daytime and is difficult to penetrate clouds, rain, smoke, etc.

(2) Near to shortwave infrared

The near to shortwave infrared (N-SWIR) wavelength is between 0.76 and 3.00 μm , which is very similar to visible light in nature. N-SWIR is a commonly used band in remote sensing technology. Because N-SWIR mainly reflects the infrared radiation of the sun from the surface and the reflective radiation characteristics of the ground objects, so it is also called reflective infrared.

(3) Medium-wave infrared spectrum band

The wavelength of the medium-wave infrared is between 3.0 and 6.0 μm . Unlike shortwave infrared reflection characteristics, medium-wave infrared is a thermal radiation. Any object in nature can radiate infrared rays when the temperature is higher than the absolute temperature ($-273.15\text{ }^{\circ}\text{C}$). The intensity of its radiant energy and the position of the spectral distribution are related to the surface state of the material, which is a function of the internal composition and temperature of the material.

The medium-infrared band of 3–5 μm is mainly used in mid-infrared remote sensing. This band is sensitive to the recognition of high-temperature targets such as fires and active volcanoes. It is often used to capture high-temperature information to identify and monitor high-temperature targets such as fires, active volcanoes, and rocket launches. Medium-wave infrared uses the thermal radiation characteristics of the ground object itself, which can work day and night, but it is also affected by atmospheric absorption and scattering. Medium-wave infrared cannot work in clouds, rain, or fog.

(4) Longwave infrared spectrum band

Longwave infrared has the longest wavelength in infrared rays, with a wavelength of 6–15 μm , and belongs to thermal radiation. In remote sensing applications, both longwave infrared and medium-wave infrared are thermal radiation, which detect the radiation of the ground objects by means of thermal induction, and are not limited by the night. Due to the long wavelength and strong penetrating capability in the atmosphere of longwave infrared rays, far-infrared photography is less affected by smoke, and the detection of low-temperature objects is more sensitive, so that a clear image can be captured through a very thick atmosphere. Since ultra-far infrared rays with a wavelength of 15 μm or more are easily absorbed by the atmosphere and water molecules, the longwave remote sensing mainly uses the band between 8 and 14 μm .

(5) Microwave band

Microwaves, also known as ultrahigh frequencies, have wavelengths between 1 and 1 m. They are divided into decimeter waves, centimeter waves, and millimeter waves in applications, and are defined as S band (10 cm), C band (5 cm), and X band (3 cm), K band (1.25 cm). Microwaves have the following characteristics that distinguish them from electromagnetic waves with other frequencies:

- (1) High-frequency properties: the microwave oscillation frequency is extremely high, more than 300 million times per second. Since the frequency is several orders of magnitude higher than that of low-frequency radio waves, some effects that are not significant in low-frequency bands can be very obvious in the microwave band. Some target characteristics, which cannot be distinguished by visible light or infrared bands, are easily distinguished by microwave remote sensing.
- (2) Shortwave properties: The wavelength of microwaves is much shorter than that of general macroscopic objects such as buildings, ships, airplanes so that significant reflections will be produced when the microwave beam is illuminated onto these objects. This feature is important for applications such as radar, navigation, and communication.
- (3) Scattering properties: when an electromagnetic wave is incident on an object, the wave will not only partly reflect along the opposite direction of the incident wave, but also scatter in other directions. Scattering is the result of interaction between incident wave and scatterer, so scattering wave carries many kinds of information about scatterers, such as frequency domain, time domain, phase, and polarization. Through the detection of scattering characteristics of different objects, the target information can be extracted, and then target recognition is carried out. This characteristic is the basis of microwave remote sensing and radar imaging.
- (4) Penetration: microwave can penetrate the upper ionosphere, and is used for satellite communication. Compared with infrared wave, microwave has a longer wavelength, less scattering, less attenuation in the atmosphere, stronger ability to penetrate clouds and rain areas. It is basically not affected by smoke, clouds, rain, and fog, with the ability of all-day and all-weather remote sensing detection.

1.2.2 Solar Radiation Characteristics

Since the temperature varies greatly along the radius of the sun and some zones of the solar atmosphere are opaque at different wavelengths, the solar radiation spectrum is complex. That is, the effective temperature of the sun is related to the wavelength. In the space outside the Earth's atmosphere, the radiance of the sun is comparable to that of a blackbody radiation source with a temperature of 5900 K. Its average radiance is $2.01 \times 10^7 \text{ W m}^{-2} \text{ sr}^{-1}$, and the average luminance is $1.95 \times 10^9 \text{ cd m}^{-2}$. A very important quantity used in global heat balance studies is the solar constant, which is

defined as the total irradiance from the sun (i.e., the integral of all wavelengths) per unit area over the average distance from the sun to the Earth and in the direction of vertical solar incidence. In 1971, the National Aeronautics and Space Administration (NASA) proposed a solar constant value of $(1\,353 \pm 21) \text{ W m}^{-2}$ as a design standard.

The energy distribution of solar radiation ranges from X-rays to the entire electromagnetic spectrum of radio waves, but 99.9% of the emitted energy is concentrated within the 0.2–10 μm wavelength interval, the maximum radiant energy is at 0.47 μm wavelength, and the energy of the ultraviolet band (wavelength is less than 0.38 μm), visible light band (wavelength from 0.38 to 0.76 μm), and the infrared band (wavelength greater than 0.76 μm) accounts for 9, 44, and 47% of the total radiant energy, respectively.

1.2.3 Interaction Between Solar Radiation and Atmosphere

For optical aerospace remote sensing of Earth observation, the radiant energy from the illumination source usually passes through the atmosphere to reach the optical remote sensor. The Earth's atmosphere is made up of various gases and aerosols. When solar rays pass through the atmosphere and reach the ground, some of the radiant energy is absorbed and scattered by the particles in the atmosphere, and the rest is transmitted to the ground. Absorption refers to the conversion of radiation energy into molecular excitation energy, while scattering refers to the redistribution of incident energy in all directions. The total impact of the absorption and scattering is a loss of a part of the incident energy, which is called the extinction. Similar situations occur when radiation from ground targets travel through the atmosphere to optical remote sensors. Figure 1.3 shows the solar spectral irradiance outside the Earth's atmosphere and at sea level.

1.2.3.1 Atmospheric Absorption Characteristics

The solar radiation will be reflected, absorbed, and scattered when passing through the atmosphere, thus attenuating the radiation intensity. The band with lighter atmospheric attenuation and higher transmittance is called the atmospheric window. For a remote sensor, only the band with high transmittance can form a good quality remote sensing image.

Because of the reflection, scattering, and absorption of the atmosphere, the attenuation of solar radiation is different in different bands, so the transmittance of each band is also different. Therefore, the detection band selected by the remote sensor should be included in the atmospheric window. The main atmospheric windows and the currently used detection bands are shown in Fig. 1.4.

- (1) 0.3–1.3 μm : This window includes partial ultraviolet band (0.30–0.38 μm), all visible light band (0.40–0.76 μm) and partial near-infrared band (0.76–1.3 μm),

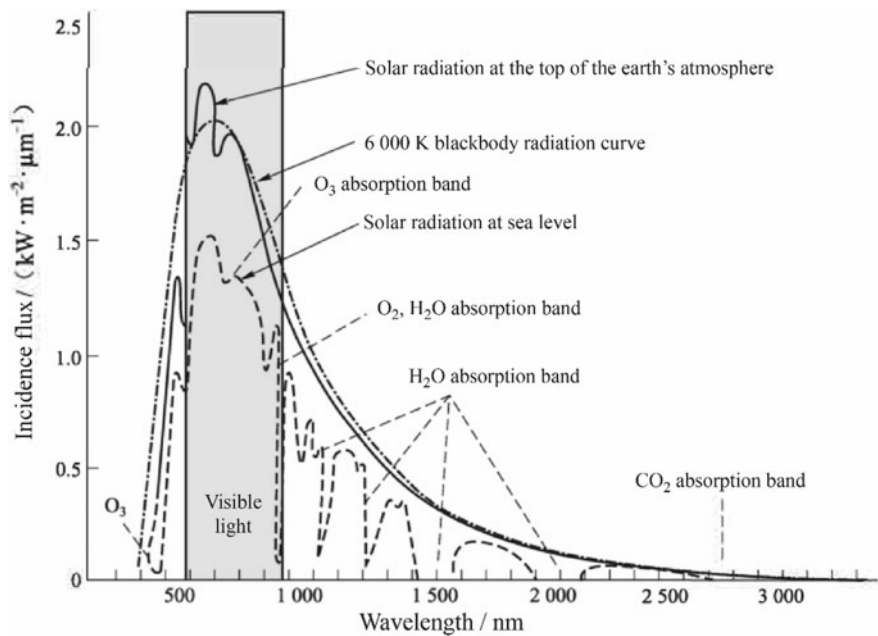


Fig. 1.3 Solar spectrum and the role of the atmosphere

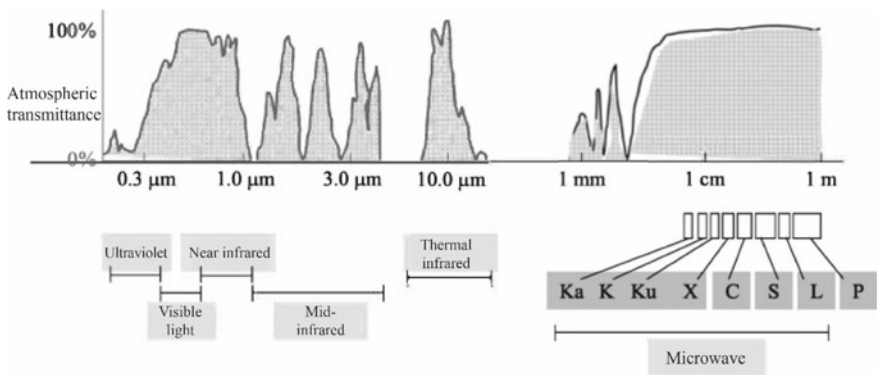


Fig. 1.4 Main atmospheric windows and detection bands

which is called reflection spectrum of ground objects. The transmittance in the window to the electromagnetic wave is over 90%.

(2) 1.5–1.8 μm and 2.0–3.5 μm : These two windows are near and shortwave infrared bands, still belong to the reflection spectrum of ground objects, and their transmittances are close to 80%. Some bands of near-infrared window have a good effect in distinguishing altered rocks, so it has great potential in remote sensing geological applications.

- (3) 3.5–5.5 μm : This window is called the mid-infrared band. The spectrum through this window can be either ground object reflection spectrum or ground object emission spectrum, which belongs to the mixed spectrum range.
- (4) 8–14 μm : This window is called the far (thermal) infrared band and is categorized as the thermal radiation spectrum. Due to the influence of ozone, water vapor, and carbon dioxide, the transmittance in this band window is only 60–70%. Since this window is the most concentrated band of thermal radiation energy at a normal temperature, it is very useful for remote sensing.
- (5) 0.8–25 cm: This window is called the microwave window and belongs to the emission spectrum range. The window is completely transparent without interference from the atmosphere and has a transmission of up to 100%. It belongs to all-weather remote sensing band.

L, C, and X bands are commonly used by satellite-borne SAR. The SAR observations in these three frequency bands are different. The specific difference is that the SAR observation in the L band has the strongest ability to penetrate the Earth's surface and is better in terrestrial biomass detection; the SAR observation in the X band is easy to implement the higher spatial resolution, so it has advantages for military target detection; the SAR observation in the C band has significant advantages for ocean target detection, such as ocean waves, internal waves, sea surface wind field, sea ice, and oil spill.

Table 1.3 Frequency band and observation element (only for reference)

Observed object	Frequency band		
	L	C	X
Sea ice	Average	Good	Very good
Freshwater ice (lakes and rivers)	Average	Unknown	Unknown
Snow (types and thickening layers)	Very good	Very good	Very good
Land humidity	Very good	Very good	Very good
Land roughness and erosion condition	Good	Very good	Very good
Soil types and characteristics	Very good	Good	Average
Land–water boundary	Very good	Good	Very good
Crop growth	Very good	Very good	Very good
Crop water content	Very good	Very good	Very good
Ocean tides and vortexes	Very good	Very good	Unknown
Surface and internal waves	Very good	Very good	Unknown
Wind waves (small waves)	Very good	Very good	Unknown
Geological structure and construction	Average	Good	Good
Desert area, lower underground	Very good	Good	Average
Vegetation/desert	Average	Good	Very good

Table 1.3 shows the applicability of the L, C, and X frequency bands commonly used in spaceborne SAR to some of the observed objects, from which the preferred frequency bands for each application area can be seen.

1.2.3.2 Atmosphere Scattering Characteristics

Scattering is the result of the interaction between electromagnetic radiation and the atmosphere. The intensity and distribution of the scattering are related to the wavelength of the electromagnetic radiation, the composition of the atmosphere, and the distance of the electromagnetic radiation through the atmosphere. Atmosphere scattering is generally divided into three types: Rayleigh, Mie Scattering, and nonselective scattering.

- (1) **Rayleigh scattering** occurs when the size of particles in the atmosphere such as gas molecules is much smaller than the wavelength of electromagnetic radiation. It is also called molecular scattering. Rayleigh scattering can be expressed as the following by Rayleigh Scattering coefficient:

$$\beta(\theta, \lambda) = \frac{2\pi^2}{N\lambda^4} [n(\lambda) - 1]^2 (1 + \cos^2 \theta), \quad (1.2)$$

where $\beta(\theta, \lambda)$ is the Rayleigh scattering coefficient, N is the number of molecules in the unit volume of the atmosphere, $n(\lambda)$ is the molecular refractive index related to the wavelength, θ is the angle between the incident electromagnetic radiation and the scattered electromagnetic radiation, and λ is the wavelength of the incident electromagnetic radiation.

In near-ultraviolet and visible spectral bands, molecular scattering is relatively large. Molecular scattering can be neglected when the wavelength exceeds 1 μm . According to Rayleigh scattering theory, the scattering of electromagnetic radiation with a shorter wavelength is stronger than that with a longer wavelength. Rayleigh scattering plays a dominant role in the upper atmosphere.

- (2) **Mie scattering** occurs when the size of particles in the atmosphere is similar to the wavelength of the incident electromagnetic radiation. Dust, smoke, and water vapor in the atmosphere are the main substances that produce Mie scattering. Compared with Rayleigh scattering, Mie scattering has a greater influence on radiation with a longer wavelength. In most cases, Mie scattering occurs in the lower atmosphere, where there are more large-scale particles.
- (3) **Nonselective scattering** occurs when the size of particles in the atmosphere is larger than the wavelength of incident electromagnetic radiation. Water droplets and large dust particles produce this scattering. The reason why it is called nonselective scattering is that it scatters almost the same radiation at all wavelengths.

The atmosphere has its own radiance by scattering. Atmosphere scattering attenuates the solar radiation directly onto the Earth's surface, and increases the hemisphere

or diffuse component, i.e., the background radiation component, which reduces the contrast of the ground objects. Atmospheric downward scattering radiation is called sky radiation (also known as sky light in the visible spectrum), while atmospheric upward scattering radiation is called atmospheric upward radiation or atmospheric pathway radiation, which can directly enter the optical remote sensor. The main effect of atmosphere scattering on remote sensing data is the increase in the radiance of atmospheric path above the radiance of the ground objects. The radiance of atmospheric path is related to various factors such as atmospheric conditions, solar zenith angle, working spectrum of optical remote sensor, observation angle, azimuth angle relative to the sun, and polarization. In fact, the position of the sun has an effect on sky radiation, ground irradiance, and atmospheric path radiance. Small-angle scattering of aerosols, especially multiple scattering, diffuses photons from the objects into many directions, thus blurring the details of the objects.

1.2.3.3 Atmospheric Refraction, Polarization, and Turbulence

In addition to scattering and absorption, the effects of the atmosphere on electromagnetic radiation include refraction, polarization, and turbulence. Atmospheric refraction may affect the geometric accuracy of images. The atmospheric refraction should be corrected for the large Field of View (FOV) of spaceborne optical remote sensor and the high requirement of geometric measurement accuracy. In addition, atmospheric polarization may affect the accuracy of radiation measurement.

Random changes of atmospheric pressure and temperature will cause random variation of atmospheric refractive index, and random fluctuations of atmospheric refractive index will lead to turbulence effects. Turbulence can cause image motion, distortion, and blur. From the perspective of imaging quality, atmospheric turbulence will affect the imaging quality of spaceborne optical remote sensor with high angular resolution.

1.2.4 Interaction Between Electromagnetic Radiation and Target

The electromagnetic radiation will interact with the target, when it irradiates on the target. These interactions include transmission, that is, part of the radiation will pass through a specific target; absorption, that is, a part of the radiation will be absorbed by the interaction of electrons or molecules in the medium encountered, and a part of the absorbed radiation energy will be re-emitted; reflection, that is, a part of the energy will be reflected (or scattered) at different angles. The dominant interaction depends mainly on the wavelength of the incident radiation and the characteristics of the target.

For satellite optical remote sensing with the sun as the illumination source, the target reflected solar radiation is detected. Target reflections can be divided into three categories, specular reflection, diffuse reflection, and mixed reflection, as shown in Fig. 1.5. The type of target reflection depends on the roughness of the target surface relative to the wavelength of the incident electromagnetic radiation. If the change in the target surface roughness is much smaller than the wavelength of the incident electromagnetic radiation, it can be considered as a smooth surface, and the target will make a specular reflection of the incident electromagnetic radiation. If the target surface is rough relative to the wavelength of the incident electromagnetic radiation, the target will diffusely reflect the incident electromagnetic radiation, which is reflected in all directions. The reflection of most actual targets presents a mixed reflection. Whether the target surface is rough or smooth is relative. For example, a surface that is smooth for longwave infrared radiation may appear rough for visible radiation.

The magnitude of the radiation energy of the target itself and its spectral distribution are related to its temperature and emissivity. For the same target, its radiation energy is mainly related to its temperature. The higher the temperature of the target, the faster the electronic vibration, and the shorter the peak wavelength of the electromagnetic energy radiated.

Different substances have different reflection and absorption characteristics in different spectral bands. The reflection spectrum of a substance is a curve of the relationship between the reflected radiation energy and the wavelength. The spectral reflectance curves of some targets are shown in Fig. 1.6. If there is an appropriate method for measuring the differences of spectral reflectance, various substances can be identified and distinguished by their relative spectral reflectance difference, which is the theoretical basis of multispectral and hyperspectral optical remote sensing.

The reflection coefficient and radiation coefficient of different ground scenes are quite different. Table 1.4 shows the reflection coefficients of some ground scenes in the visible spectrum ($0.4\text{--}0.7\text{ }\mu\text{m}$). The radiation coefficient of some ground objects in different spectral bands is given in Table 1.5.

The electromagnetic radiation characteristics such as size, shape, spectral reflectance, temperature, spectral emissivity, and the difference between target and

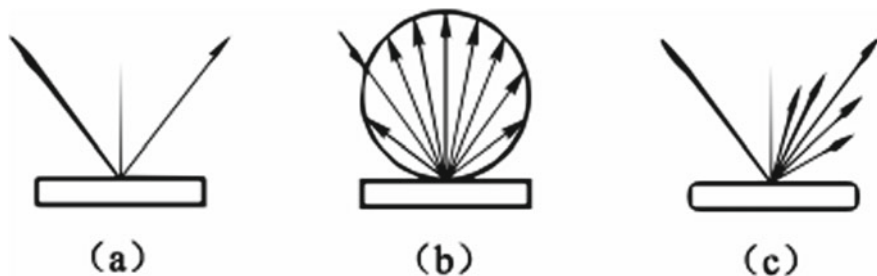


Fig. 1.5 Target reflection type. **a** Specular reflection. **b** Diffuse reflection. **c** Mixed reflection

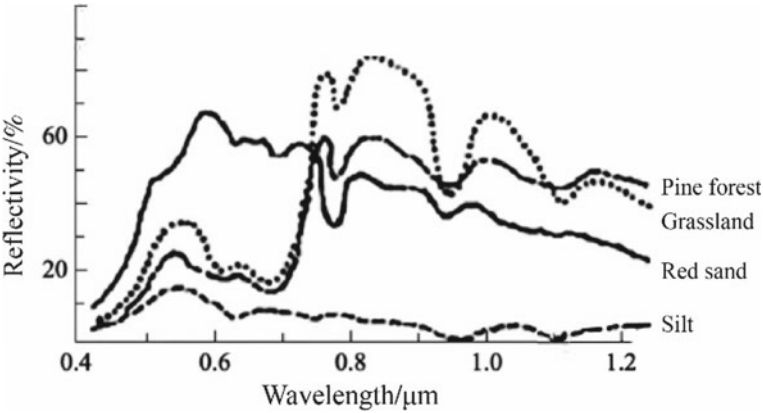


Fig. 1.6 Spectral reflectance curves of some typical targets

Table 1.4 Reflection coefficients of some ground covers (0.4–0.7 μm)

Ground covers	Cover reflection coefficient	
	Dry	Wet
Yellow sand	0.31	0.18
Clay	0.15	0.08
Green grass	0.14	0.09
Black soil	0.07	0.05
Concrete	0.17	0.10
Asphalt	0.10	0.07
Snow	0.78	–

Table 1.5 Average radiation coefficients of some ground covers in different wavebands

Ground covers	Radiation coefficient in different wavebands		
	1.8–2.7 μm	3–5 μm	8–13 μm
Green leaf	0.84	0.90	0.92
Dry leaf	0.82	0.94	0.96
Flattened maple leaf	0.58	0.87	0.92
Green leaves (a great amount)	0.67	0.90	0.92
Green coniferous branches	0.86	0.96	0.97
Hay	0.62	0.82	0.88
Various kinds of sand	0.54–0.62	0.64–0.82	0.92–0.98
Bark	0.75–0.78	0.87–0.90	0.94–0.97

background are the key factors of remote sensing detection, which also determines the design of remote sensors and the interpretation ability of remote sensing images.

1.3 Terrestrial Environment

1.3.1 Analysis of Satellite On-Orbit Environment and Effect

In terms of remote sensing satellites, the terrestrial space environment during orbital operation consists of many threatening elements such as solar electromagnetic radiation, vacuum, charged particle radiation in space, Earth atmosphere, and atomic oxygen. These elements will interact with satellites operating in low Earth orbit individually or jointly, resulting in various space environment effects that affect the safe operation of satellites.

1.3.2 Charged Particle Radiation Environment

1.3.2.1 Earth Radiation Belt

The Earth radiation belt refers to a zone of highly charged particles captured by the geomagnetic field in the terrestrial space, also known as the Van Allen radiation belt. The shape of the radiation belt is roughly similar to the circular structure around the Earth over the equator. The intensity of the radiation belt is obviously concentrated in two zones, the inner radiation belt (an altitude of 600–10,000 km) and the outer radiation belt (an altitude of 10,000–60,000 km). As shown in Fig. 1.7, the edge of the radiation belt is also generally consistent with the magnetic line, because the charged particles that make up the radiation belt move along the magnetic line of the Earth's magnetic field. Due to the asymmetry of the magnetopause, the magnetic field of the magnetosphere is asymmetrical, which causes the radiation belt slightly different between the dayside and the night side.

1.3.2.2 Solar Cosmic Ray Environment

Solar cosmic rays are high-energy particle streams from the sun, which occur during short-term variations of the solar activity cycle. The solar cosmic rays are mainly composed of protons and heavy ions, whose energy ranges from 10 MeV to tens of GeV. Typical solar energy particle events are also known as solar proton events because they mainly contain high-energy protons. The occurrence of solar proton events is highly random. Statistical results show that there are more solar proton events near the peak year of solar activity, which occur more than 10 times a year.

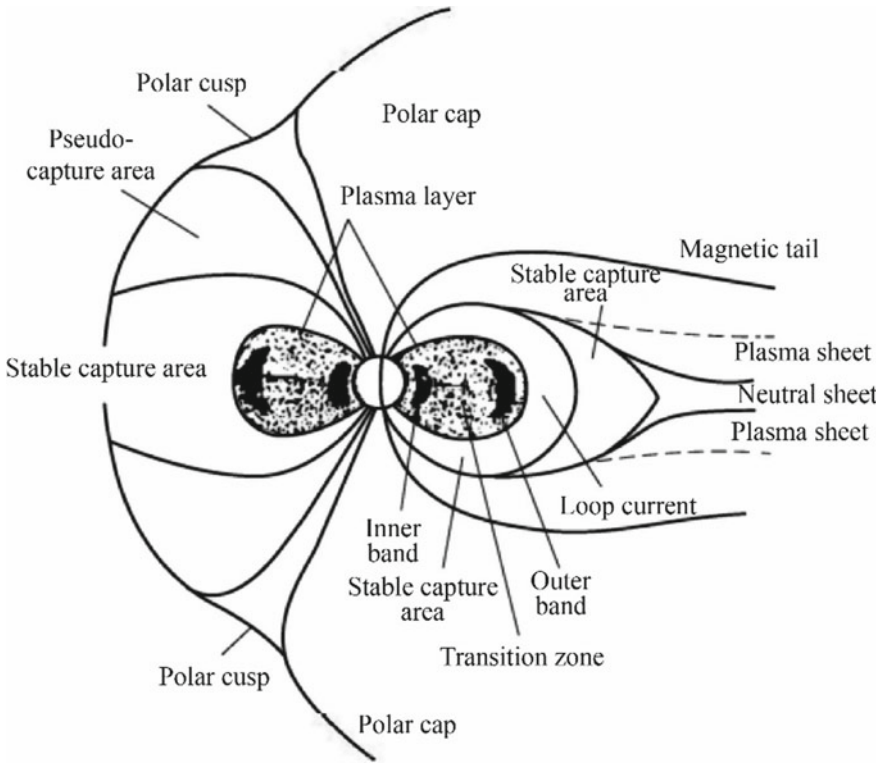


Fig. 1.7 Schematic diagram of the Earth radiation belt structure

Because of the occasional characteristics of solar proton events, sometimes not once in several months, sometimes several times in a month; in the low year of solar activity, the probability of solar proton events is seldom, usually only 3 or 4 times a year, or even less.

1.3.2.3 Galactic Cosmic Ray Environment

Cosmic ray, usually known as “galactic cosmic rays”, is charged particles with low flux but high energy from galaxies outside the solar system. The energy range of the particles is generally 10^2 MeV– 10^9 GeV. Most of the energy of the particles are concentrated in the range of 10^3 – 10^7 MeV, and the flux in free space is only 0.2 – 0.4 ($\text{cm}^2 \text{ Sr s}$) $^{-1}$. Galactic cosmic rays contain almost all elements in the periodic table of elements, but the main component is protons, accounting for 84.3% of the total, followed by alpha particles, accounting for 14.4% of the total, and other heavy nuclei accounting for 1.3% of the total.

1.3.2.4 Solar Wind

Solar wind is a kind of rarefied high-temperature plasma that originates from corona. When temperature increases, particles of corona escape from solar gravitational constrain in all directions, which result in the solar wind.

The main components of solar wind are electrons and protons, accounting for more than 95%, heavy ions, accounting for about 4.8%, which are mainly helium ions, and a small amount of other components, such as oxygen ions, and iron ions. The velocity of solar wind is not uniform in space, and can reach 900 km/s at high speed and 200 km/s at low speed. The solar wind particle density fluctuates greatly, the average density is $10^6/\text{m}^3$, and the average solar wind magnetic field is about 6 nT.

1.3.3 Vacuum

During the launch of the satellite, the atmospheric pressure encountered by the satellite began to drop sharply from 1 atm, and finally reached a very high vacuum level. The effects of vacuum environment on satellites:

- (a) the heat exchange between components can only be carried out by conduction and radiation;
- (b) the volatile substances on the surface or inside of materials can be diffused or sublimated into the surrounding environment to produce vacuum exhaust, resulting in changes in material properties;
- (c) molecules generated from the vacuum venting of materials can deposit on the surface of thermal control materials or optical devices, causing molecular contamination;
- (d) the vacuum discharge can occur between two electrodes at low pressure;
- (e) the vacuum dry friction and cold welding can occur between solid surfaces relative motion, etc.

1.3.4 Neutral Atmosphere

Neutral atmosphere is the unique space environment encountered by spacecraft in Low Earth Orbit (LEO), in which the atmospheric thermosphere and outer atmosphere are in the height range of 100–1000 km. Therefore, the neutral atmosphere mainly affects the LEO satellites. The Medium Earth Orbit (MEO), Geostationary Earth Orbit (GEO), and Inclined Geosynchronous Satellite Orbit (IGSO) satellites are less affected by the neutral atmosphere, because their orbital altitudes are far from the affected area of the neutral atmosphere. The impact of the neutral atmosphere on spacecraft mainly includes two aspects. One is the resistance of atmospheric density to spacecraft, which will lead to the change of spacecraft service life, orbit

decay rate, and attitude; the other is atomic oxygen in the upper atmosphere, as a strong oxidant, that has chemical effects with spacecraft surface materials (such as oxidation, sputtering, corrosion, hollowing), thus resulting in mass loss of spacecraft surface materials, surface erosion, and physical and chemical performance changes.

1.3.5 Solar Electromagnetic Radiation

Solar electromagnetic radiation refers to the output of the sun within the electromagnetic spectrum. The electromagnetic radiation environment in satellite orbit includes X-ray, ultraviolet, visible, infrared, and radio waves from the sun. The solar irradiance in orbit is closely related to the external heat flow received by satellites and solar cell power generation efficiency; solar ultraviolet irradiation may cause the performance deterioration of the satellites outer surface materials; other electromagnetic environments may cause background noise and stray light interference on satellite wireless communications, optical sensors, optical cameras, etc. Although the proportion of solar ultraviolet radiation flux in total flux is very small, the ultraviolet radiation has a short wavelength and large light quantum energy, which can cause radiation damage to some materials on the surface of spacecraft. The most vulnerable materials are optical materials, organic materials, etc. Moreover, solar radiation may have a variety of effects on satellite temperature control system, energy system, attitude control system, communication system, and so on.

1.3.6 Solar Disturbance

Solar disturbances, also known as solar storm, emit usually large amounts of matter and energy into space in the form of electromagnetic radiation, high-energy charged particle radiation, and high-speed plasma clouds (Fig. 1.8). Strong solar storms occur usually in three energy forms at the same time, and will reach the Earth space one after another with their different propagation velocities in interplanetary space, which will affect spacecraft in different orbits.

When the solar storm occurs, the intensity of electromagnetic radiation with various bands from the sun increases sharply, while the intensity of electromagnetic radiation in the radio, ultraviolet, and X-ray bands increase by several orders of magnitude, directly acting on the upper atmosphere and the ionosphere of the Earth, resulting in the significantly increased atmospheric resistance on spacecraft operating in LEO. In addition, the sharp increase in the concentration of free electrons in the ionosphere on the dayside will affect the propagation of radio waves.

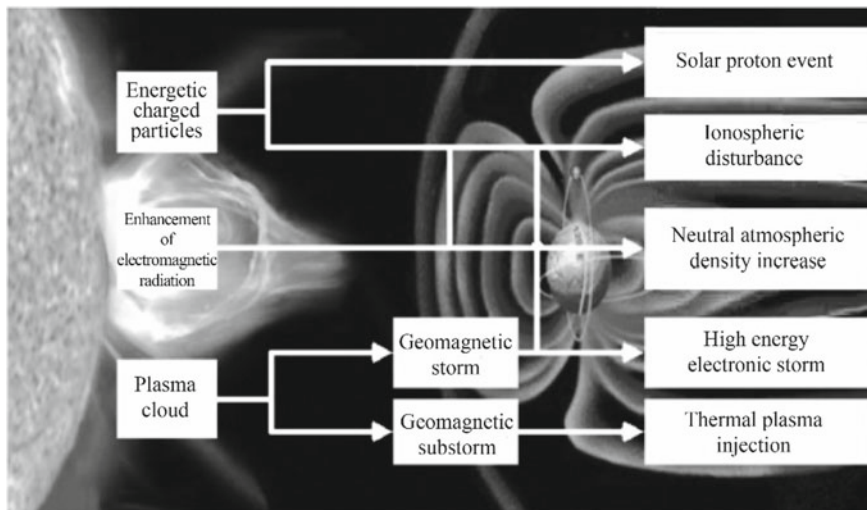


Fig. 1.8 Schematic diagram of the effects of solar disturbance on terrestrial space environment, reprinted from Ref. [1], copyright 2012, with permission from National Defense Industry Press

1.3.7 Total Dose Effect of Space Radiation

When charged particles are incident on an object (absorber), part of or all of their energy will transfer to the absorber. When absorbers are electronic components and materials used by satellites, they will be damaged by total dose radiation, which is called the total dose effect.

Different types of electronic components and materials on satellites exhibit different damage phenomena under the total ionizing dose radiation of charged particles in space. After the absorption of certain space radiation doses on orbit, the following damage may occur on most electronic components and materials:

- (a) glass materials will darken after serious irradiation, and the transmittance will be decreased;
- (b) the emissivity and absorption rate of thermal control materials will be changed;
- (c) the physical and mechanical properties of organic materials will be degraded;
- (d) the performance of semiconductor devices will deteriorate, such as the decrease of current amplification coefficient of bipolar transistors, reverse breakdown voltage, transconductance of unipolar device (MOS device), the increase of threshold voltage drift, leakage current and input misalignment of operational amplifier, the decrease of open-loop gain, the change of the common-mode rejection ratio, the increase of the dark current and background noise of photoelectric device and other semiconductor detectors;

- (e) for spaceborne computers and other systems, the increase of radiation dose will lead to the gradual deviation of the electrical performance parameters of logic devices, such as CPU and its chips, and eventually lead to the logical function errors or even loss.

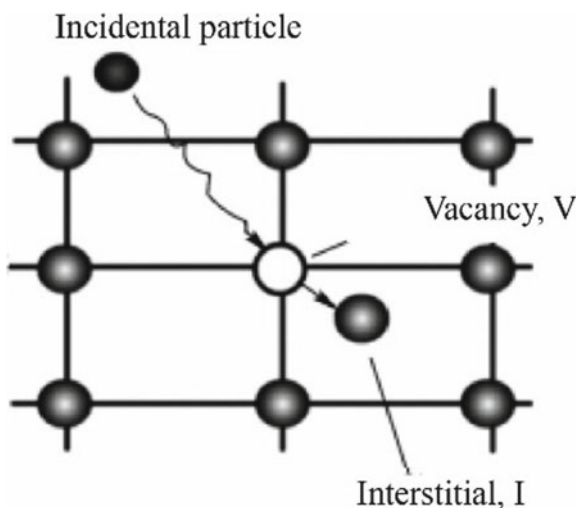
During the on-orbit operation of remote sensing satellite, the main contributions to the total space radiation dose are the components of charged particles with low energy, high flux, and long-acting time, which mainly include the electrons and protons captured in the radiation belt of the Earth.

1.3.8 Spatial Displacement Effect

When space-charged particles are incident on satellite electronic components, besides the total ionization dose produced by ionization, there will also be displacement effect, that is, the incident energetic particles bombard the absorber atoms and cause them to move out of the original position of the lattice, thus resulting in lattice defects, finally causing damage to satellite electronic components. The overall consequence of displacement is to damage the lifetime or mobility of minority carriers in semiconductor materials, and increasing the background noise, dark current, and leakage current of devices. A schematic diagram of the lattice atomic displacements caused by incident particles is shown in Fig. 1.9.

Displacement damage will affect the performance of a few carriers, such as photoelectric devices, bipolar devices, and solar cells. It is characterized in that the current gain of bipolar devices decreases, especially at low current (PNP devices are more sensitive to displacement damage than NPN devices); the leakage current of diodes,

Fig. 1.9 Schema diagram of lattice atom displacement caused by incident particles



forward conduction voltage drop and the dark current and hot spots increase; the charge transfer efficiency of Charge Coupled Device (CCD) decreases.

The solar cells on remote sensing satellites are damaged by the displacement effect under the radiation of trapped electrons and protons as well as solar flare protons in the radiation belt of the Earth, resulting in the decrease of short-circuit current, open-circuit voltage, and output power of the solar cells.

1.3.9 Spatial Single Event Effect

Single event effect is a radiation effect caused by a single high-energy proton or heavy ion incident on an electronic device. According to the different effect mechanisms, radiation effect can be divided into single event upset, Single Event Latch-up (SEL), single event burnout, single event gate rupture, and single event transient.

From the background of space radiation environment in remote sensing satellite orbit, the protons captured in the radiation belts, protons and heavy ions of solar cosmic rays, and galactic cosmic rays are the particle source that produces single event effect.

Single event upset is a charged particles' radiation effect occurring in logic devices and circuits with monostable or bistable states. When a single space energetic charged particle bombards a large-scale or ultra-large-scale logic microelectronic device chip, ionization effect occurs along the incident trajectory of the particle in the zone near the PN junction inside the chip, generating a certain number of electron-hole pairs (carriers). If the chip is in the power-on state at this time, these carriers generated by radiation will drift and redistribute under the action of electric field inside the chip, thus changing the normal carrier distribution and motion state inside the chip. When this change is significant enough, the electrical performance state of the device will be changed, resulting in logical errors of devices or circuits, such as data reversal in memory units ("1" to "0" or "0" to "1"), which may lead to data processing errors, confusion of circuit logic functions and computer instruction flow. These can cause a programs fleet, so that the errors in various satellites monitoring data may result from a minor incident, and the wrong instruction implemented by satellite may result from a big one, causing satellites to be in orbital anomalies and malfunctions, and even making the satellites in a catastrophic situation. In less serious cases, errors will be caused in various satellite monitoring data, and in serious cases, erroneous commands will be executed by satellites, thus causing satellite in abnormalities and faults on-orbit, and even making satellites to be in a catastrophic situation.

SEL is a very harmful space radiation effect occurring in Complementary Metal-Oxide-Semiconductor (CMOS) processing devices, as shown in Fig. 1.10. Charged particles bombard CMOS devices, and then a large number of electron-hole pairs are ionized along the particle trajectory. When these carriers are collected by sensitive PN junctions in the chip through drift and diffusion, parasitic Silicon Controlled Rectifier (SCR) structures in SOI CMOS devices may turn on and trigger latch-up of SOI CMOS devices. SEL in CMOS devices may cause three hazards to satellites:

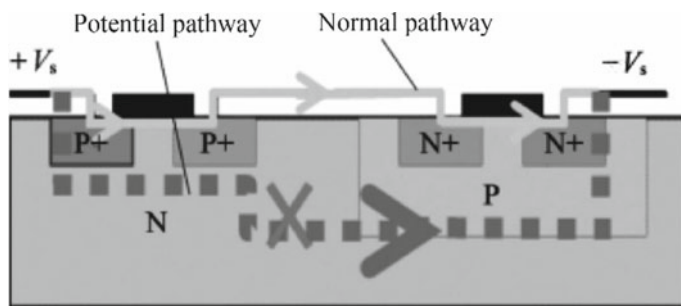


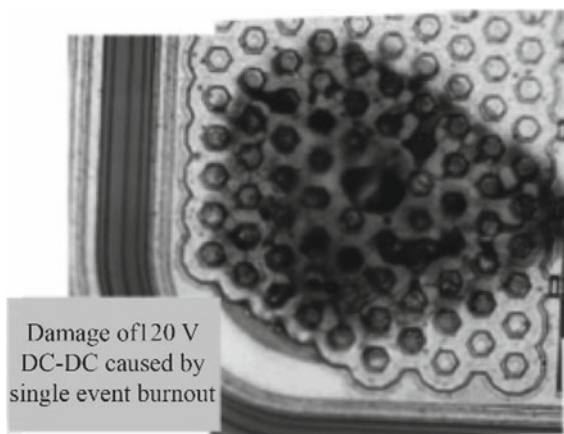
Fig. 1.10 Structure diagram of SOI CMOS devices, reprinted from Ref. [1], copyright 2012, with permission from National Defense Industry Press

first, the devices and instruments that are locked may be burned down by the high current (hundreds of mA or even several A); second, the spaceborne secondary power supply used by the device may be damaged by the sudden increase of the load current; and third, when the output voltage of the second power supply used by the device is changed due to the latch-up, the operation of other onboard instruments using the same secondary power supply may be affected.

Single event burnout is a spatial radiation effect mainly occurring in power MOS devices (such as VDMOSFET), as shown in Fig. 1.11. Charge avalanche multiplication mechanism is one of the important theoretical models to explain single event burnout. The parasitic bipolar transistor between the drain and source of VDMOSFET can be turned on under the incidence of high-energy particles, resulting in a large drain-source current, which in turn causes the device to be burned out.

Single event gate breakdown is a spatial radiation effect occurring in power MOS devices (such as VDMOSFET), as shown in Fig. 1.12. When a high-energy charged particle in space incidents and penetrates its gate, gate oxide, and device substrate, a

Fig. 1.11 Schematic diagram of burnout of DC power converter caused by single event burnout, reprinted from Ref. [1], copyright 2012, with permission from National Defense Industry Press



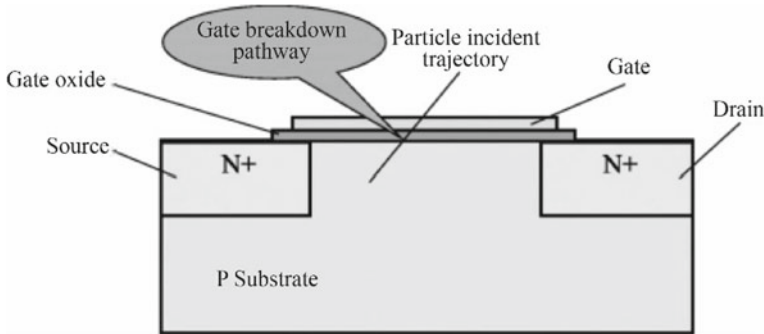


Fig. 1.12 Schematic diagram of single event gate breakdown mechanism

large number of electrons and positive ions will be generated through the ionization effect on the Si side of the Si-SiO₂ interface along the incident trajectory of the particle in a MOS device in the normal operating state, resulting in a concentration of charges and an enhanced electric field. When the latter exceeds the insulating strength of gate oxide (SiO₂), the permanent breakdown of gate oxide may occur, which will lead to the complete failure of devices.

1.4 Introduction to Satellite Remote Sensing Engineering System

Space Engineering covers a wide range and is a large-scale system engineering, which is also known as “space large-scale system engineering”. Space engineering includes launch vehicle, spacecraft launch site, Telemetry, Track and Command (TT&C) network, ground application system, astronaut system, return landing site, etc., for details, see Fig. 1.13. For application satellites, it generally includes the following subsystems:

(1) Remote Sensing Satellite System

Satellites are composed of multiple systems to meet a variety of space mission requirements. These systems can be divided into two broad categories: payload and support platform of satellite. For remote sensing satellite, the payload refers to the optical camera, SAR, and data processing and transmission system of remote sensing satellite. In addition to the payload, other devices, which form various functional systems to support the work of the payloads, are collectively known as the satellite platform (also called support platform). The satellite platform mainly consists of control, TT&C, spaceborne data management, power supply, structure, thermal control, propulsion, and other subsystems, which form a whole to guarantee payload operation and normal satellite operation.

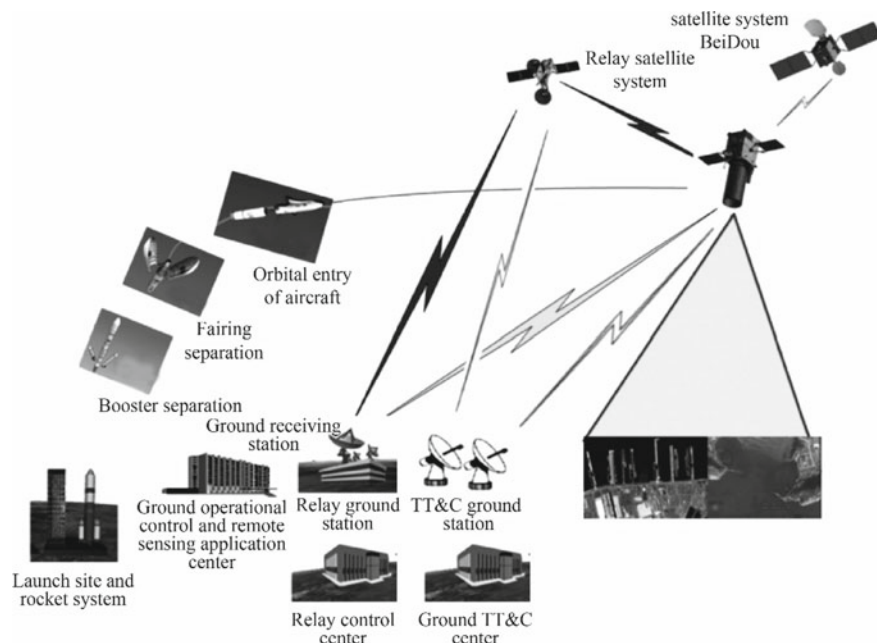


Fig. 1.13 Schematic diagram of large-scale space system engineering

(2) Launch Vehicle System

The satellite is launched into a predetermined orbit by a launch vehicle. From take-off at the launch site to orbit entry, this route and its trajectory are called launch orbit. The operating phase of the rocket engine in launch orbit is called powered phase, and the inertial flight phase after engine stops is called free flight phase or inertial flight phase. Because the weight and orbit requirements of spacecraft for different missions vary greatly, it is necessary to select an appropriate launch vehicle and a suitable launch site for launching, so the type of launch vehicle for satellite launching is the first thing to consider and determine. China's "Long March" series rockets basically cover low, medium, and high Earth orbit, which could meet the launching requirements of different spacecraft.

(3) Launch Site System

The selection of launch site is mainly based on satellite mission requirements, rocket selection, and satellite overall parameters, especially satellite orbit requirements, followed by the compatibility between the launch vehicle and launch site. Four launch sites (centers) have been built in China, including the Space Launch Center Jiuquan, Xichang, Taiyuan, and Wenchang in the province Hainan, from which hundreds of satellites have been successfully launched.

(4) Engineering TT&C System

Satellite TT&C system is the main means of communication between satellite and ground station, which tracks, measures, and monitors the flight orbit, attitude, and working state of orbiting satellite. As the satellite is launched into the orbit with the launch vehicle, the ground station measures the satellite orbit in time and masters the working conditions of the satellite platform and payload and its engineering parameters, and performs mission control of the satellite. The functions of satellite TT&C system include tracking and orbit measurement, telemetry, and remote control. The task of tracking and orbit measurement is to realize the functions of angle measurement, distance measurement, and velocity measurement of satellite. The above three functions form an unification in satellite TT&C system.

Navigation Satellite System BeiDou (BD) and Global Position System (GPS) provide real-time positioning, orbit determination, and original measurement data for remote sensing satellite. Remote sensing satellite receives Beidou navigation or compatible GPS satellite signals and performs high-precision orbit determination processing. High-precision orbit determination data are used as auxiliary data of remote sensing satellite payload to improve the positioning accuracy of image preprocessing. In addition, the high-precision timing function of the navigation system Beidou is used to provide the high-precision timing service on the spaceborne time system, and the real-time and high-precision orbit parameters are provided for spaceborne control system by high-precision orbit calculation of navigation receiver.

(5) Remote Sensing Satellite Operational Control System

Satellite operational control system, an integrated mission management control center and a nerve center of satellite remote sensing engineering system, is mainly used for comprehensive planning the satellite remote sensing imaging tasks, overall scheduling the satellite and ground resources, centralized receiving and effective managing of remote sensing data, to ensure the coordinated and efficient operation of the whole system. The operation control system consists of various subsystems such as mission planning, command and dispatch, mission control, information transmission, and data reception.

(6) Remote Sensing Satellite Application System

The main task of the remote sensing satellite application system is to complete the processing of various types of satellite remote sensing data, accurately and quickly generate remote sensing images, perform calibration and quality assessment, and provide information services for national and user decision-making. The application system generally consists of systems such as integrated management, information processing, production, coordinate determination testing, and quality evaluation. For the interface requirements of satellite and application systems, the following items shall be described: the main technical indicators of satellite, satellite coordinate system, main tasks/functions/tactical index of operation control and application

system, camera imaging characteristics (including imaging control, geometric characteristics, radiation characteristics, working mode, etc.), image data transmission characteristics (including compression coding, frequency characteristics, modulation mode, coding mode, antenna usage, auxiliary data transmission format, data transmission AOS format, etc.), satellite operating mode, satellite time synchronization system, satellite remote control and telemetry, etc.

(7) Relay TT&C and High-Speed Data Transmission System

Tracking and Data Relay Satellite System (TDRSS) is a communication satellite system, which transmits the tracking and control signals of low and medium orbit satellites and the TT&C information and high-speed image data sent back by satellites to the Earth station. Space-based TT&C communication and data transmission system is characterized by high orbital coverage, multi-target TT&C, and high-speed data transmission. The integration of TT&C and data transmission is realized by full digital synthesis, which significantly improves the corresponding ability and effectiveness of TT&C and high-speed data transmission tasks of low and medium orbit satellites.

Reference

1. D. Yu, Z. Cai, X. Wei et al., *Impact of Solar Storm on Spacecraft and Prevention* (National Defense Industry Press, Beijing, 2012)

Chapter 2

Space Orbit Design of Remote Sensing Satellite



2.1 Overview

2.1.1 *Classification by Orbit Altitude*

The atmosphere on the ground is as high as 160 km, above which the atmosphere becomes thinner and eventually reaches space. As shown in Table 2.1, Earth satellites are classified according to their typical parameters.

In the design of LEO and MEO orbital parameters, the radiation belts around the Earth (1.3–1.7 times the radius of the Earth and 3.1–4.1 times the radius of the Earth) shall be avoided. The typical LEO satellite is at about 500–1500 km above the Earth, with an orbital period of 1.5–2.0 h. Typical MEO satellites altitudes range from 5000 to 12,000 km above Earth in which a satellite's orbital period is several hours. In a highly elliptical orbit, the spacecraft can see polar regions in most orbital cycle time. Typical highly elliptic orbit such as Molniya orbits is an elliptic orbit with a perigee of 1000 km, an apogee of 39,400 km, an inclination of 63.4°, and a period of about 12 h. The GEO satellite travels from west to east at an altitude of 35,786 km above Earth with a design orbital period of 24 h, thus remaining stationary relative to the Earth.

2.1.2 *Classification by Orbital Characteristics*

The satellites orbiting the Earth will be affected by the Earth's noncentral gravity, solar–lunar gravity, atmospheric resistance, and other perturbation forces, in which the noncentral gravity of the Earth causing the perturbation of orbital elements is the maximum perturbation factor. Several special types of orbits can be designed by adopting the effects of the Earth's noncentral gravitational perturbation. These orbits will be briefly introduced in this section.

Table 2.1 Classification of Earth orbits

Orbital type	Abbreviation	Orbit altitude (km)	Eccentricity	Inclination (°)	Orbital period
Geostationary orbit	GEO	35,786	0	0	1 sidereal day
Geosynchronous orbit	GEO		Close to 0	0–90	1 sidereal day
Highly elliptical orbit	HEO		≥ 0.25 to <1	0–90	
Medium Earth orbit	MEO	2000–30,000	0 to high	0–90	
Low Earth orbit	LEO	200–2000	0 to high	0–90	>90 min

2.1.2.1 Sun-Synchronous Orbit

The Sun-synchronous orbit refers to the orbit with the plane precession angular velocity same as the average angular velocity of the sun moving in the ecliptic.

The orbital inclination of the Sun-synchronous orbit i can be obtained by the following formula:

$$\cos i = -n_s \left(\frac{3}{2} J_2 \frac{R_E^2}{p^2} n \right)^{-1}, \quad (2.1)$$

where n_s is the average angular velocity of the sun; n is the orbital average angular velocity of the satellite; J_2 represents the Earth perturbation term; $p = a(1 - e^2)$, where e is the eccentricity, a is the semimajor axis of the satellite orbit; and R_E is Earth's equatorial radius.

The Sun-synchronous orbit is a retrograde orbit if its inclination is greater than 90° . Taking the Sun-synchronous circular orbit of 500–1000 km as an example, the orbital inclination is at 97.4 – 99.47° . The Sun-synchronous orbit has two characteristics: the first is that the satellites in the Sun-synchronous orbits have the same local time over the same latitude in rising (or descending) section of each lap, and the local time of descending section of each lap passing over the equator is LTDN; the second is that the angle between the sunray and the orbital plane varies slightly.

The Sun-synchronous orbit can place a satellite in more stable lighting due to its these two characteristics, which is conducive to satellite energy, thermal control, and attitude control, so reducing the complexity of satellite system. The change of the sun elevation of the sub-satellite point of the Sun-synchronous orbit is not significant, which is beneficial to the optical imaging of Earth observation, therefore widely used by remote sensing satellites.

In practice, the Sun-synchronous orbit with LTDN at 10:30 and 13:30 are mostly used by the optical remote sensing satellites, while the Sun-synchronous orbit with LTDN at 6:00 and 18:00 are used by more microwave remote sensing satellites.

2.1.2.2 Orbit with Critical Inclination

Critical inclination orbit is the orbit with an inclination equal to $63^{\circ}26'$ or $116^{\circ}34'$. The change rate of the argument of perigee and the eccentricity of the orbit with critical inclination are close to zero, and the stability of satellite on this orbit will be limited by the orbital eccentricity. The greater the eccentricity, the better the stability is. Due to stationary apsidal lines of the orbit with critical inclination, it can be guaranteed that the perigee or the apogee is always located at the certain latitude.

2.1.2.3 Recursive Orbit

Recursive orbit refers to the orbit on which satellite's the sub-satellite point trajectories overlaps every certain laps.

Let the time interval of one revolution precession of the orbit relative to the Earth's surface be T_e , and the satellite orbital period (generally referred to as the nodal period) be T_{Ω} . If there are integers D and N (D and N are prime numbers), which satisfy the following:

$$N \cdot T_{\Omega} = D \cdot T_e, \quad (2.2)$$

then after D days and just after running N laps, the satellite's ground trace begins to repeat. Such orbit is called as a recursive orbit.

For some census-type remote sensing satellites, such as surveying and mapping satellites, regular sub-satellite point imaging to the same target is required. The characteristics of the regular repeat of the ground trace of the orbit sub-satellite point just meet the requirements of this mission. Therefore, this type of satellite usually chooses the Sun-synchronous recursive orbit, which combines both the characteristics of sun synchronization and recursive orbit.

2.1.2.4 Frozen Orbit

The frozen orbit refers to the orbit whose change rate of the argument of perigee and eccentricity are both zero. In general, the frozen orbit contains an arch geostationary orbit with an arbitrary inclination. Different from the critical inclination orbit introduced in the previous, the frozen orbit is not limited to a specific inclination. For LEO satellites, there are two possibilities for the corresponding frozen orbit, that is, orbits with an argument of perigee $\omega = 90^{\circ}$ or $\omega = 270^{\circ}$.

If the semimajor axis of and the inclination of the orbit are given, the corresponding frozen orbit eccentricity can be uniquely determined. For LEOs with a general inclination, the order of magnitude of the frozen orbit eccentricity is below one-thousandth.

Satellites on frozen orbit are at constant altitude when passing through the same latitude area at different times. With this feature, the image scale can be obtained by

remote sensing satellites to be consistent, thus facilitating the stitching and comparison of images at different times, and playing a core role in Earth observation. For example, this orbit was selected by China’s ZY-1 satellite series.

Characteristics of the Sun-synchronous orbit, the recursive orbit, and the frozen orbit are different. The orbits of Earth remote sensing satellites can have the characteristics of any one or two or even all three orbits.

2.2 Design Requirements and Characteristics of Remote Sensing Satellite Orbits

At present, imaging remote sensing satellites, such as optical remote sensing satellites and microwave remote sensing satellites, are dominated in the worldwide on-orbit remote sensing satellites, which operate mainly in low Earth orbit for obtaining the target imagery in high spatial resolution. A major trend of its development is that the requirements of resolution are getting higher and higher, and the requirements of revisit time are getting shorter and shorter. Therefore, optical and microwave remote sensing satellites combining both high resolution and fast revisit are the typical representatives of current remote sensing satellites. This chapter focuses on the orbit design methods of these two types of remote sensing satellites.

2.2.1 Orbit Design Analysis of Optical Remote Sensing Satellite

At present, the main parameters of worldwide high-resolution optical remote sensing satellites are shown in Table 2.2.

It can be found that the worldwide main high-resolution optical remote sensing satellites are dominated by the Sun-synchronous orbit with LTDN at 10:30, and there are also cases where the Sun-synchronous orbits with LTDN at 13:30 have been selected. In determining the orbit altitude, higher orbit altitude and greater

Table 2.2 Main parameters of worldwide high-resolution optical remote sensing satellites

Satellite	Country	Launch time	Orbit altitude (km)	LTDN	Resolution at sub-satellite point (m)
GeoEye—1	USA	2008	684	10:30	0.41
World View—2	USA	2009	770	10:30	0.46
World View—3	USA	2014	617	10:30/13:30	0.31
World View—4	USA	2016	617	10:30/13:30	0.31
Pleiades—1	France	2011	694	10:30	0.50

attitude maneuverability should be adopted on the premise of implementing the high-resolution requirement, thereby improving the revisit ability.

For optical remote sensing satellites with a wide variety of kinds and a wide range of applications, their orbit design depends largely on mission and application requirements. This section focuses on the analysis of mission requirements and orbital design characteristics of high-resolution optical remote sensing satellites.

2.2.1.1 Mission Requirement Analysis

According to the application characteristics of high-resolution optical remote sensing satellite, the main mission requirements are as follows:

(a) Application requirement for global coverage

The latitude coverage of satellite depends mostly on the orbit inclination. The attitude maneuverability can increase the latitude coverage but the capacity is limited. Therefore, global coverage generally requires polar or near-polar orbit.

(b) Requirement on high resolution, large swath, and fast revisit

When the pixel size and focal length of the optical camera are determined, the higher the orbit altitude is, the lower the resolution is. For high-resolution optical remote sensing satellites, due to the high Ground Sampling Distance (GSD) requirement and the constraints of its optical field of view, the imaging swath of the camera is generally small, usually several kilometers to more than ten kilometers. For such remote sensing satellite, repeated sub-satellite point observation of global targets will lead to a very long recursive period, so that rapid revisit is generally achieved through altitude maneuvers. The revisit ability of satellite revisit depends on both the orbit altitude and attitude maneuverability. For a satellite at an altitude of 500 km, 5-day revisit can be achieved by attitude side-sway ($\pm 35^\circ$), while 1-day revisit can be realized by attitude side-sway ($\pm 60^\circ$) for a satellite at an altitude of 680 km.

(c) Requirement on lighting conditions

When optical imaging of ground targets is carried out, the ground targets shall satisfy certain lighting conditions, that is, to meet the requirements of sun elevation angle. The sun elevation angle refers to the elevation angle of the sun's rays relative to the local horizon. The sun elevation is an important parameter of optical imaging remote sensing, which is usually between 10° and 70° . From this perspective, the selection of an orbit with stable lighting condition is very important for optical imaging remote sensing satellites.

(d) Requirement of orbit maneuver and maintenance

The design life of optical remote sensing satellites is generally at least 5 years. LEO satellites are affected by atmospheric drag, and its altitude will decrease continuously,

so regular orbit maintenance is required. The lower the orbit altitude, the more fuel is used for maintaining the orbit altitude. Therefore, when selecting the orbit altitude, the factor of satellite propellant carrying capacity shall be taken into account.

2.2.1.2 Analysis of Orbit Design

(a) Preference for the Sun-synchronous orbit with the LTDN at 10:30 or 13:30

The Sun-synchronous orbit is a near-polar orbit. Its greatest advantage is that it can satisfy both the requirements of the global coverage and the imaging lighting condition of optical remote sensing satellites, and is also conducive to the integrated design, especially satellite energy security, because the angle between the sunray and the orbital plane changes little.

Optical remote sensing satellites use more Sun-synchronous orbits with the LTDN of 10:30 and 13:30. This is because the orbit with these two LTDNs corresponds to the widest area that satisfies the imaging lighting conditions and has the largest number of imaging days in a year.

For the application of multi-satellite network, the multi-satellite network with the same LTDN (i.e., on the same orbit plane) may limit the improvement of the efficiency of revisit. Therefore, it is necessary to relax the constraints of imaging sun elevation angle and increase the deployment at LTDN. In general, the LTDN is selected from the range of 09:00 to 15:00.

(b) Comprehensive tradeoff between orbit altitude and resolution

For optical cameras, the resolution depends directly on the orbit altitude. High-resolution optical remote sensing satellites usually operate in low Earth orbit to obtain a high spatial resolution of targets. The range of orbit altitude should be limited according to the requirements of resolution and lifetime of the satellite. If the satellite is required to achieve higher resolution, it can be achieved by reducing the orbit altitude while the camera focal length and pixel size remain unchanged, such as 0.2 m resolution at 500 km. When the orbit altitude is reduced to 250 km, the spatial resolution can be increased to 0.1 m. However, it is very difficult to design and operate the whole satellite system with a circular orbit of 250–300 km, which causes a series of problems, such as the sharp increase of fuel consumption, the shortening of data transmission arc, and the reduction of integration time. The best way to solve the contradiction between resolution and fuel consumption is to select elliptical orbit to achieve high-resolution imaging at perigee, and to reduce atmospheric density and electromagnetic environment impact by setting apogee altitude.

(c) Large-range attitude maneuver for fast revisit

For high-resolution optical remote sensing satellites, fast revisit is achieved mainly through large-range attitude maneuver. The orbit altitude is determined according to the revisit time and attitude maneuver ability given. In the selection of orbit altitude,

many countries prefer to improve the ability of revisit by increasing orbit altitude and enhancing satellite attitude maneuverability, while China is inclined to improve resolution.

(d) Multi-mission orbits and multi-satellite network

To improve the adaptability and performance of high-resolution optical sensing satellites, it is necessary that the satellites can adapt to a variety of temporal or spatial resolutions. In order to meet the requirement of this mission, abandoning the usual design ideas in the past, multi-mission orbits for a satellite can be designed. Generally, mission orbits include normal orbit and emergency orbit. Satellites can transfer from normal orbit to emergency orbit or vice versa by orbit maneuver. Satellites usually operate in the normal orbit and, if necessary, can quickly transfer onto emergency orbit to increase temporal or spatial resolution.

Some high-resolution optical remote sensing satellites in China usually use the Sun-synchronous circular orbit of about 500 km as the normal orbit, and the 568 km daily circular recursive orbit as the emergency orbit. This application can better satisfy the requirements of imaging resolution, revisit time, and key targets imaging.

With the increase of satellite attitude and orbit maneuverability, the emergency orbit can also be elliptical orbit or a daily revisited orbit. The indicator that can be achieved by satellites are no longer strongly constrained by the altitude of the orbit. The adaptability of spatial resolution and temporal resolution of satellite has been greatly enhanced, thus accomplishing the mission of multiple observations.

- (i) Satellites operating in elliptical orbits can achieve higher resolution at perigee and wide-area coverage at apogee. By optimizing the orbit maneuver time sequence, perigee alignment to target area can be achieved quickly, which cracks hard nuts of multitask and complex application requirements.
- (ii) Daily revisit orbits can achieve an image of any global target at least once a day. If the attitude maneuverability is increased to $\pm 60^\circ$, the orbit with an altitude greater than 680 km can meet the requirement of daily revisit.

In addition to improving orbit altitude and attitude maneuverability of the satellite, multi-satellite networking is another effective means to improve mission revisit time on the premise of ensuring certain spatial resolution. Satellite networking can be divided into coplanar constellation and noncoplanar constellation. If the number of satellites in coplanar constellation can ensure that the system revisit time is better than 1 day, only the addition of satellites in noncoplanar constellation can further reduce the system revisit period.

2.2.2 Orbit Design Analysis of Microwave Remote Sensing Satellite

Microwave remote sensing satellites include synthetic aperture radar satellite and other microwave payload satellites. The worldwide typical microwave remote sensing satellites are shown in Table 2.3.

It can be concluded that the main international microwave remote sensing satellite is mainly for global coverage remote sensing imaging, and most of them choose Sun-synchronous dawn–dusk orbit. The Sun-synchronous dawn–dusk orbit and inclined orbit are mainly chosen for non-imaging microwave remote sensing satellites, such as ocean dynamic environment satellite. This section focuses on the analysis of the mission requirements and orbit design of high-resolution SAR satellites.

2.2.2.1 Mission Analysis

(a) High-resolution requirements

For high-resolution SAR satellites, there is no direct geometric relationship between their spatial resolution and orbit altitude. The imaging resolution of SAR payload is

Table 2.3 Main parameters of some microwave remote sensing satellites worldwide

Satellite name	Country	Launch year	Orbit altitude (km)	Orbit type	Main indicators (m)	Main payload
COSMO-SkyMed	Italy	2007	620	SSO/18:00	Resolution 0.7	SAR
TerraSAR	Germany	2007	514	SSO/06:00	Resolution 1.0	SAR
Tandem SAR	Germany	2010	514	SSO/06:00	Resolution 1.0	SAR
SAR-Lupe	Germany	2008	500	Near-polar orbit	Resolution 0.5	SAR
TecSAR	Israel	2008	550	Inclination: 143.3°	Resolution 1.0	SAR
Jason-3	USA	2016	1343	Inclination: 66°	Height accuracy 0.04	Radar altimeter/microwave radiometer
HY-2	China	2011	971	SSO/06:00	Height accuracy 0.06	Radar altimeter/microwave radiometer/microwave scatterometer
GF-3	China	2016	705	SSO/06:00	Resolution 1.0	SAR

directly related to the payload power, which is inversely proportional to the fourth power of the imaging distance, so the orbital height indirectly affects the imaging resolution to some extent. For satellites with SAR as the main payload, the imaging resolution, orbit altitude, and satellite power shall be optimized.

(b) Global observing requirements

The observing range of high-resolution SAR satellites depends primarily on the orbital inclination and the visual coverage capability of the SAR payload, while the visual coverage capability of the SAR payload depends on the incident angle range. For global observing, general SAR satellites still prefer to Sun-synchronous orbit. However, due to the large clutter interference at the sub-satellite point, the SAR payload cannot directly image the sub-satellite point, thus forming a blind spot at the sub-satellite point. When selecting the Sun-synchronous orbit for SAR satellites, the distribution of sub-satellite point track should be taken into account, and the observation of sub-satellite point blind spot shall be performed by using an adjacent track to ensure global seamless coverage requirements.

(c) Wide field of view and fast revisit requirements

Unlike the optical cameras with single and fixed swath, SAR payloads have multiple modes of operation, such as scanning, striping, bunching, and spot beam mode, each with different imaging resolution and imaging swath. In order to meet the wide field of view requirements of specific tasks, some operating modes have an imaging swath of several hundred kilometers. SAR satellites can carry out different angle observations by electric scanning of payloads, while the most high-resolution SAR satellites have the ability to realize left and right dual-sided view through attitude maneuvering. The dual-sided view ability doubles the satellite's scope of observation to meet the requirements of fast revisit.

(d) No requirements on lighting conditions for imaging

SAR satellites differ from optical camera satellites in that their payloads imaging does not depend on the lighting conditions of the ground target, and the satellite does not have to choose a Sun-synchronous orbit. Since the Sun-synchronous orbit is conducive to the integrated design of satellites, especially the design requirements of on-satellite energy, control and thermal control subsystems, and the orbital inclination of close to 90° is conducive to global observing imaging, the global observing SAR satellites are generally required to choose the Sun-synchronous orbit, and the Local Time of Descend Node (LTDN) shall be selected and determined according to the specific mission.

(e) High load power consumption, high requirements for satellite energy

SAR payload operates by transmitting electromagnetic wave signals and receiving reflected signals from targets. Therefore, SAR payload needs more energy than

optical remote sensing satellite, and its power consumption is very high. The sun lighting condition of satellite on orbit shall be fully considered in the design of the orbit.

2.2.2.2 Analysis of Orbit Design

- (a) Sun synchronous orbit with the LTDN 06:00 and 18:00 is preferred

For SAR satellites on the Sun-synchronous orbit with global observation requirements, global observation can be achieved with the electrical scanning capability of the payload itself. Because the satellite has no requirement on lighting condition for imaging target, and the Sun-synchronous orbit with LTDNs 06:00 and 18:00 can provide the satellite with a full-light condition for most of the year, which is conducive to the design of satellite energy system, and is a common orbit for global coverage of microwave remote sensing satellites.

- (b) Quick revisit and wide field of view by attitude maneuver

For the mission requirements of quick revisit and wide field of view, satellites can operate by changing the incidence angle of SAR payload, adjusting the beam width and dual-sided view. SAR payload usually has multiple operating modes, some of which can achieve an instantaneous swath of several hundred kilometers, thus meeting the requirement of wide field of view.

SAR payload antenna can be divided into two types, namely, phased array antenna and reflector antenna. Phased array antenna SAR imaging system can realize the rapid conversion of beam pointing by electronic control, which makes the antenna to quickly adjust pointing imaging, but attitude maneuver is also required for dual-sided view imaging. The reflector antenna system realizes the beam scanning required for imaging by satellite attitude maneuvering. Therefore, different antenna systems used in the satellite SAR payload have different requirements for satellite attitude maneuverability. The phased array antenna can meet the requirement of quick revisit through dual-sided view imaging, and the reflector antenna is used to realize the required beam, which requires the satellite to have agile attitude maneuverability.

- (c) Frozen and repeat orbit for interferometry or measurement of marine dynamic environment factors

Generally, SAR payload satellites shall satisfy multi-mission requirements for imaging, surface deformation measurement, etc. The measurement of surface deformation is performed by the interferometric capabilities of SAR payload. According to the requirements of interferometry, satellite orbit altitude and sub-sat track drift shall be within a certain range. The frozen orbit is characterized by fixed argument of perigee, zero orbit eccentricity change rate, and small altitude change of satellite passing through the same latitude. The characteristics of repeat orbit are the repetition of the sub-satellite track after a specific time. The characteristics of these two

orbits just meet the requirements of interferometry. Therefore, the frozen repeat orbit is usually used for SAR payload satellites.

2.3 Analysis and Design of Multi-mission Orbits for Optical Remote Sensing Satellite

2.3.1 Orbit Selection Principle

The mission requirements of high-resolution optical remote sensing satellite mainly include high resolution and fast revisit, large-range attitude maneuver to achieve high revisit due to small imaging swath, and using elliptical orbit characteristics to solve the application requirements of multi-mission.

The Sun-synchronous recursive orbit is usually adopted. Once the orbit type is determined, the orbit parameters shall be determined based on requirements such as resolution, swath, revisit, and sun elevation.

- (1) GSD: The condition that the orbit altitude H shall satisfy is $H \leq (\text{GSD} \times \text{focal length/pixel size})$.
- (2) Imaging swath: The imaging swath depends on the camera's field of view angle, the number of effective pixels and the orbit altitude. A higher orbit altitude is selected to obtain a larger swath, which increases the target imaging area of a single strip.
- (3) Coverage and revisit characteristics: Orbit altitude directly determines the distribution characteristics of the ground trace. When selecting orbit altitude, it is necessary to select the appropriate orbit altitude according to the attitude maneuverability, thus optimizing the coverage and revisit performance.
- (4) Orbit maintenance and maneuverability: Satellite orbit maintenance in lower orbit altitude and orbital maneuver in larger range consume more fuel, so it is necessary to take into account the satellite fuel-carrying capacity and fuel consumption requirements during the lifetime.
- (5) LTDN: The imaging lighting and solar wing lighting conditions are determined by this factor, and the selection should take the use of multi-satellite networks and the platform adaptability into account.
- (6) Emergency orbit maneuver applications: The selection of emergency orbit altitude shall meet the high resolution or fast revisit imaging requirements of the emergency events, such as regional geological disasters, that is, to meet the fuel budget requirements for normal/emergency orbit transfer and maintenance.

2.3.2 Satellite Multi-mission Orbit Design

2.3.2.1 Satellite Orbit Altitude Design

In order to meet the requirements of satellite imaging resolution, revisit efficiency, and fuel consumption for long-term orbit maintenance, satellite orbit can be designed into two types: normal orbit and emergency orbit. The former is based on the principle of low fuel consumption and high efficiency of revisit to ensure that the satellite can operate stably on this orbit for a long time. The latter is mainly required to achieve high spatial resolution or high temporal resolution.

This strategy can take full advantage of different altitude orbits, not only ensure that satellites can acquire ultra-high-resolution images on low orbit, but also save satellite fuel consumption on higher orbit and enable satellites to have higher coverage capacity, thus improving the overall effectiveness of the whole life cycle.

(a) Selection of the normal orbit altitude

Fuel requirements for orbit altitude maintenance depend specifically on the intensity of solar activity and the surface-to-mass ratio of satellites. For satellites with orbit altitude of about 500 km, annual fuel consumption for orbit altitude maintenance is about several to tens of kilograms, which is acceptable from the perspective of long-term stable on-orbit operation. The revisit efficiency is highly correlated with satellite orbit altitude, but it is not that the higher the orbit, the better the revisit efficiency. The sub-satellite point ground trace distribution of satellite on 490 km orbit is more uniform, so its revisit time is shorter than that of a satellite on 500 km orbit under the same attitude side-sway ability.

(b) Emergency orbit altitude design

The main requirement of emergency orbits is to achieve high spatial resolution or high temporal resolution. High spatial resolution can be achieved by lowering the orbit altitude. If the resolution of 0.3 m can be achieved at 490 km altitude, the resolution can be reduced by half when the altitude of orbit is reduced to 250 km. However, the use of circular orbits as low as 250–300 km will lead to a series of problems, such as a sharp increase in fuel consumption, the shortening of data transmission arc, and a reduction in integration time. The design and operation of the whole satellite system will be an arduous task. Therefore, the orbit altitude and resolution shall be weighed comprehensively according to the specific flight mission. Taking fuel consumption as an example, for 250 km circular orbit, the fuel consumption required to maintain orbit altitude is 100 times that of 490 km circular orbit. For a typical large-scale remote sensing satellite in China, it means a few tons of fuel consumption per year.

The best way to solve the significant contradiction between resolution and fuel consumption is to select elliptical orbit, so as to achieve high-resolution imaging at perigee, while reducing atmospheric density and electromagnetic environment impact by setting apogee altitude. In order to improve the spatial resolution, the

perigee altitude is about 250 km, and the apogee altitude can be selected in the range of 500–1000 km according to the optimum design of the carrying capacity of launch vehicle, the efficiency of revisit, and the lifetime. When satellite transfers from the normal orbit to the emergency orbit, the perigee can be quickly located above the target area by optimizing the orbit maneuver timing.

In order to achieve an emergency orbit with high time resolution, the orbit altitude can be increased. If 568 km daily recursive circular orbit is used as emergency orbit, the target of key area can be revisited once a day, and the size of the observation area depends on the attitude maneuver ability. On the 680 km orbit, satellite with $\pm 60^\circ$ attitude maneuver ability can revisit the global arbitrary target once a day.

2.3.2.2 Design of LTDN

The imaging lighting and solar wing lighting conditions are determined by LTDN. According to the requirement of the range of sun elevation angle from 10° to 70° for optical camera imaging, and under comprehensive consideration of the design result of energy system and thermal control system, the Sun-synchronous orbit with LTDN at 10:30 or 13:30 is preferentially chosen by most optical remote sensing satellites in China, and meets the requirement of the maximum number of days in a year to meet imaging lighting conditions. Considering the use of multiple satellite networks and the adaptability of the platform in the future, the LTDN shall be selected from 09:00 to 15:00 as required.

2.3.3 Design of Satellite Multi-mission Orbit Parameters

According to the design and analysis of satellite multi-mission orbit, in view of the application requirements of a high-resolution remote sensing satellite model, the multi-mission orbit design scheme is as follows: if the circular orbit of 490 km is selected as normal orbit to achieve a GSD of 0.3–0.5 m; if the elliptical orbit of 250 km $\times$ 490 km is selected, the GSD will be further improved to 0.15–0.25 m GSD at the perigee; if the daily recursive circular orbit of 568 km is selected, satellite can revisit the hot spot area once a day; if the elliptical orbit of 490 km $\times$ 680 km is selected, the satellite with $\pm 60^\circ$ attitude maneuver ability can revisit the target in the hot spot area once a day at the apogee, and every 4 days at perigee. The specific orbit parameters are shown in Table 2.4.

2.3.4 Orbit Control

Orbit control of optical remote sensing satellite mainly includes initial orbit adjustment, orbit maintenance, orbit transfer, etc.

Table 2.4 Multi-mission orbit design parameters ($\pm 60^\circ$ attitude maneuver ability)

Parameters	Orbit type			
	Normal orbit	Emergency orbit		
	Recursive circular orbit	Elliptical orbit	Recursive circular orbit	Elliptical orbit
Orbit altitude (km)	490.335	250–490	568.143	490–680
Orbit semimajor axis (km)	6861.335	6741	6939.143	6956
Inclination ($^\circ$)	97.3617	97.2883	97.6952	97.7218
Eccentricity	0	0.0178	0	0.0137
LTDN	09.00–15.00	09.00–15.00	09.00–15.00	09.00–15.00
Nodal period (min)	94.393	91.9327	96	96.3498
Revisit time	3–4 days	5 days at perigee 4 days at apogee	Daily recursive	4 days at perigee 1 day at apogee

2.3.4.1 Initial Orbit Adjustment

In order to enter the target orbit, satellites shall use their own propulsion system for orbit control after injection due to the factors such as the launch vehicle’s injection error. In this stage, it is necessary to adjust and control the semimajor axis and the inclination of the orbit. When adjusting the semimajor axis, the eccentricity is corrected as needed. In addition, if a frozen orbit is adopted, there are special requirements for eccentricity and argument of perigee. It is also necessary to adjust the eccentricity and the argument of perigee in place while controlling the semimajor axis of orbit.

2.3.4.2 Orbit Maintenance

(a) Ground Trace Maintenance

Due to the influence of atmospheric drag, the orbit altitude of NEOS will decrease continuously. The resulting shortening of the orbital period will drift the position of ground trace eastward, and the repeatability of the trace is destroyed. This is why periodic trace maintenance is required.

The task of ground trace maintenance is to control the ground trace within a certain width centered on the nominal position, which is performed by adjusting the semimajor axis, thus the semimajor axis is also maintained. For example, for an optical remote sensing satellite on the Sun-synchronous orbit with an orbit altitude of 490 km, assuming that the mission requires that sub-satellite point ground trace

Table 2.5 Theoretical adjustment and orbit control frequency of typical optical remote sensing satellites

Solar activity rate	Atmospheric density (kg km ⁻³)	Semimajor axis change rate (m d ⁻¹)	Semimajor axis adjustment (m)	Orbit control period (d)
High ($F_{10.7} = 225$)	3.90E-03	339.62	4316.02	12.71
Medium ($F_{10.7} = 150$)	1.60E-03	139.33	2764.46	19.84
Low ($F_{10.7} = 75$)	1.25E-04	-10.89	772.69	70.98

is maintained within ± 30 km and the windward area to the mass ratio of the satellite is 0.007 m²/kg, the corresponding trace maintenance is shown in Table 2.5.

(b) Maintenance of Orbital Eccentricity and Argument of Perigee

The altitude maintenance of elliptical orbit is similar to that of near-circular orbit, but perigee altitude and apogee altitude shall be maintained by choosing appropriate orbit maneuver position. According to the mission requirements, argument of perigee of the elliptical orbit shall be also maintained. In order to adjust the perigee to the desired target position, the ellipse arch shall be rotated at a certain angle. For the specific orbit control strategy, please refer to “Spacecraft Orbital Dynamics and Control” edited by Yang Jiachi. For the case of an elliptical orbit of 250 km × 700 km, the velocity increment required to adjust the argument of perigee by 10° is about 17.7 m/s.

When satellites do not maneuver on the elliptical orbit, due to the perturbation of the orbit, the arch of the orbit will rotate in the inertial space for more than one hundred days. During this period, the perigee position will appear passively twice at any latitude, so it can make full use of this characteristic to image with high resolution in some areas at specified latitude.

2.3.4.3 Orbit Transfer

According to the different requirements of imaging range and revisit efficiency of optical remote sensing satellites, satellite flies on different mission orbits in different periods, and transfers between them by orbit maneuver, including the transfer between circular orbits, the transfer between circular orbits and elliptical orbits. By the orbit maneuver, while raising (lowering) the altitude of the orbit, in some cases, it is necessary to arrange a certain ground trace of the target trace at a specific position, so that the imaging arc passes through a specific target area, which can be achieved by the starting and stopping time, the time of orbit maneuver, and the value of each orbit maneuver.

2.3.5 Orbit Control Fuel Consumption

For the typical applications mentioned above, the fuel consumption for different orbit maintenance and inter-orbit maneuver is shown in Table 2.6. It can be seen from the table that elliptical orbits with apogee altitudes of several hundred kilometers, such as 250 km × 490 km elliptical orbits, are more suitable for emergency orbits when fuel carrying capacity is limited.

When the apogee altitude of the elliptic orbit is higher than the average altitude of the circular orbit, using that attenuation speed of the elliptical orbital apogee is much larger than that of the perigee, the apogee maneuver adjustment from elliptic orbit to circular orbit can be completed by natural apogee attenuation, which can save fuel consumption for altitude maintenance of elliptic orbit and orbit maneuver.

The fuel consumption for orbital maintenance on elliptical orbit with perigee of 250 km is huge. Properly increasing the perigee height can significantly reduce the fuel consumption for orbital maintenance. If the elliptical orbit of 250 km × 490 km is changed to 300 km × 490 km, the fuel consumption for orbit maintenance can be reduced from 476 to 170 kg per year.

Table 2.6 Fuel consumption analysis of different orbital maintenance and inter-orbit maneuver

Orbit control operation	Orbit parameter (km)	Fuel consumption	Remarks
Temporary orbit maintenance	250 × 250	1900 kg per year	Keep fuel consumption at an average level
Normal orbit maintenance	490 × 490	19.00 kg per year	
Emergency orbit maintenance	250 × 490	476.00 kg per year	
	568 × 568	5.16 kg per year	–
	680 × 680	1.25 kg per year	–
Normal → Emergency orbit maneuver	490 × 490 → 250 × 490	81.75 kg	–
	490 × 490 → 568 × 568	53.50 kg	–
	490 × 490 → 490 × 680	84.68 kg	Daily regional revisit nearly 1 month can be achieved by targeting the apogee on the hotspot target

Note In the table above, the specific impulse of the engine is assumed as 290 s and the windward area is 25 m². The satellite weight change caused by orbital maneuver is not considered in this analysis. Fuel consumption analysis is carried out based on satellite weight of 3550 kg

2.3.6 Mission Application Strategy

2.3.6.1 Strategies for the Use of High Spatial Resolution Orbits

For the typical application flight mission requirements in this book, taking the fuel constraint of 600 kg as an example, more fuel will be consumed due to both the emergency orbit maneuver and orbit maintenance, and the following two options should be considered under the constraints of fuel and engine impulses. Firstly, the elliptical orbit shall be selected for the emergency orbit. After the completion of emergency mission, the apogee maneuver adjustment from the elliptical orbit to the normal circular orbit should be completed by using the natural attenuation of the elliptical orbital apogee proposed in Sect. 2.3.5. Secondly, the apogee of emergency orbit should be kept in line with that of normal orbit, and the application times of multi-mission orbit should be increased as much as possible under the premise of reducing the fuel consumption of orbit maneuver. In summary, the following mission program can be determined.

It takes about 4 months that the apogee altitude is naturally attenuated to 490 km, when the satellite is launched into $250 \text{ km} \times 680 \text{ km}$ orbit. During this period, the image with the GSD of 0.15–0.25 m is acquired at the perigee, and then the satellite is raised into $490 \text{ km} \times 490 \text{ km}$ circular orbit, on which satellite stably operates for a long time, and the image with GSD of 0.3–0.5 m is acquired. The satellite can maneuver as needed into $250 \text{ km} \times 490 \text{ km}$ orbit, and obtains image with the GSD of 0.15–0.25 m. For two roundtrips, satellite consumes fuel of 600 kg. Detailed strategies for the use of satellite orbit are shown in Table 2.7.

The transition from initial orbit to normal orbit is assisted by altitude attenuation caused by atmospheric drag, which saves fuel for orbit maneuver. The two roundtrips from normal orbit to emergency orbit are realized by direct orbit maneuver. In order to save the fuel consumption for emergency orbit altitude maintenance, satellite stays on emergency orbit for 1 month in the year of high solar activity and for 2 months in the year of low solar activity. According to this strategy, satellite consumes fuel of 600 kg for two roundtrips between normal and $250 \text{ km} \times 490 \text{ km}$ emergency orbit with a fuel remaining of 37.53 kg.

2.3.6.2 Strategies for the Use of High-Time-Resolution Orbit

The orbit altitude shall be increased for imaging with high-time resolution on emergency orbit, and the fuel consumption for orbit maintenance will be significantly reduced with the increase of orbit altitude. Therefore, the main factor to be considered in the strategy of high-time-resolution orbit operation is the fuel consumption of orbit maneuver. Taking 600 kg fuel constraints as an example, the following mission schemes are comprehensively determined with the aim of improving the application capability of multi-mission orbit as much as possible due to the fuel limit and specific impulse of the engine.

Table 2.7 Strategies of orbit use

Segment	Orbit (km)	Orbit control operation	Duration	Fuel consumption (kg)	Remarks
Segment of injection	250×680	Correction of injection error	Orbit maneuver	17.65	
Month 1–4	$250 \times 680 \rightarrow 250 \times 490$	Correcting the apogee natural attenuation caused by the orbit error	4–7 months	4.44	2015, $F_{10.7}$ range 70–100
Month 5	$250 \times 490 \rightarrow 490 \times 490$	Initial $\rightarrow$ normal orbit	Orbit maneuver	81.22	Maneuvering to normal orbit
Month 5 to year 5	490×490	Normal orbit maintenance	4 years and 5 months	49.46	Year of high and medium + medium and low solar activity
	$490 \times 490 \rightarrow 250 \times 490$	Normal $\rightarrow$ emergency orbit maneuver	Orbit maneuver	78.13	The first emergency orbit maneuver
	250×490	Emergency orbit maintenance	2 months	42.33	Year of low solar activity
	$250 \times 490 \rightarrow 490 \times 490$	Emergency $\rightarrow$ normal orbit maneuver	Orbit maneuver	75.27	Return to normal orbit
	$490 \times 490 \rightarrow 250 \times 490$	Normal $\rightarrow$ Emergency orbit maneuver	Orbit maneuver	73.49	The second emergency orbit
	250×490	Emergency orbit maintenance	1 month	39.67	Year of high solar activity
	$250 \times 490 \rightarrow 490 \times 490$	Emergency $\rightarrow$ normal orbit maneuver	Orbit maneuver	70.81	Return to normal orbit
Attitude control over the life cycle				30.00	
Total over the life cycle				562.47	

On the $490\text{ km} \times 490\text{ km}$ circular orbit, the satellite can revisit in every 4-day and image with the GSD of 0.3–0.5 min long-term; The satellite can maneuver as needed and transfer into 568 km daily recursive orbit to achieve daily revisits in specific target areas, but its coverage has a “watermelon peel pattern like” leakage; if the satellite transfers into $490\text{ km} \times 680\text{ km}$ orbit on demand, its arc around the apogee has achieved daily revisit any target area in the world. Its advantage is that there is no “watermelon peel pattern like” leakage in 568 km daily recursive orbit.

2.3.7 Design of Initial Orbit Offset

2.3.7.1 Semimajor Axis Offset

For the semimajor axis, the attenuation caused by injection error and atmospheric drag shall be adjusted by orbit maneuver. For satellites whose attitude maneuverability is limited and the thruster cannot directly provide negative velocity increment, the semimajor axis of initial orbit will be offset negatively, while other satellites generally do not consider the initial orbit offset.

2.3.7.2 Inclination Offset

Due to the influence of solar gravity, the orbit inclination will be changed for a long time during the operating lifetime of the satellite (Fig. 2.1), which will affect the maintenance of solar synchronization. In order to minimize this effect, the orbit

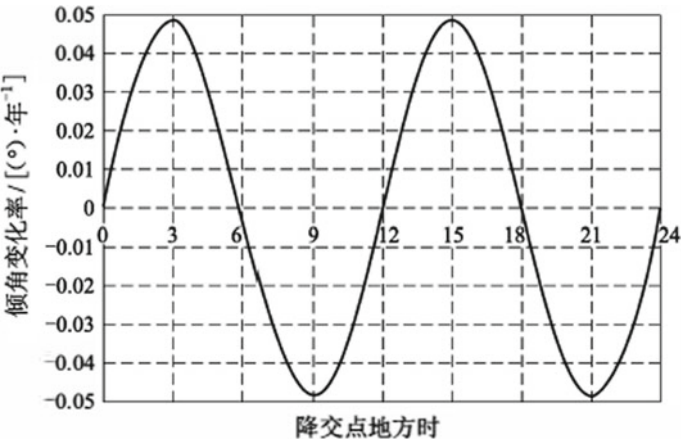


Fig. 2.1 Effect of solar gravitational perturbation on orbits with different LTDN

inclination is properly offset. For a Sun-synchronous orbit, this change can be approximated as a linear change over a long period of time. This book generally applies the normal orbit, so this change is -0.0312° per year. This change will cause the LTDN to drift continuously toward the 6 o'clock direction.

Taking satellite's 5-year service life as an example, in order to minimize the variation range of the LTDN, the injection offset of the inclination should be 0.064° .

2.3.7.3 Offset of LTDN

Different average orbital semimajor axes have different inclination angles. For satellites with multi-mission orbits, in order to ensure the characteristics of Sun-synchronous orbit, the inclination must be adjusted during orbit maneuver. For the $250\text{ km} \times 490\text{ km}$ elliptical orbit and 490 km circular orbit, the difference of orbital inclination is 0.0734° . Based on the mass of 3550 kg and the specific impulse of 290 s , 14 kg of fuel is consumed for the adjustment of this difference of orbital inclination.

If the inclination is not adjusted to save fuel, for an orbit with 10:30 am LTDN, the LTDN will increase by 20 min after the 4 months of initial orbit operation.

If the nominal LTDN is 10:30 am, the initial LTDN shall be set at 10:10 am. After 4 months of satellite's initial orbit operation, the LTDN just increases to the nominal value. The initial LTDN will be the nominal value if satellite transfers into the normal orbit at this point.

2.3.8 Drift Characteristics of LTDN

The following factors should be taken into account for the LTDN drifts of high-resolution optical remote sensing satellite:

- (a) Orbital attenuation effect: Assuming that the nominal LTDN is 10:30 am, according to the design results in Sect. 2.3.7, the initial LTDN is set at 10:10 am. After 4 months of satellite's initial orbit operation, the LTDN just increases to the nominal value. The satellite transfers into the normal orbit at this point, so that the initial LTDN will be the nominal value.
- (b) The influence of inclination change: Because of solar gravitational perturbation, the orbit inclination will be changed, which changes the LTDN. If the initial inclination is offset by 0.064° , for an orbit with an LTDN of 10:30 am, the cumulative change of the LTDN is approximately $\pm 18\text{ min}$ over 5 years.
- (c) The influence of orbit maneuver: if satellite transfers from normal orbit to emergency orbit without the inclination adjustment to save fuel, for example, the orbit maneuver from the 490 km orbit to $250\text{ km} \times 680\text{ km}$ orbit will last 4 months, so that its LTDN will increase by 17 min for the orbit with LTDN of 10:30 am.

- (d) Influence of the launch window: Considering that the zero-window launch may not be possible due to various reasons, if the satellite is launched in advance, the injection LTDN will be earlier, and if the satellite is launched late, the LTDN will be delayed.
- (e) Total drift range: assuming that the launch window ranges from 0 to +5 min. Taking the orbit with the LTDN of 10:30 am as an example, the satellite's LTDN varies totally from 10:10 to 11:10 am.

2.3.9 Design of Resolution and Revisit Ability

Taking 490 km circular orbit with the GSD of 0.3 m as an example, for 4 mission orbits given for the typical application in this book, their main coverage characteristics are analyzed as shown in Table 2.8.

It can be seen that, with $\pm 60^\circ$ attitude maneuver, the satellite on the 568 km daily recursive orbit can realize daily revisit for the specific target area; the satellite on the 680 km circular orbit can achieve daily revisits for any region in the world. On a 490 km circular orbit, the satellite can revisit any region of the world every 4 days, with a GSD of 0.3 m. On a $250 \text{ km} \times 490 \text{ km}$ elliptical orbit, the satellite can revisit every 7 days at perigee, with a GSD of 0.15 m. Figure 2.2 shows the observation of a specific area by the satellite on the 568 km daily recursive orbit.

Table 2.8 Main coverage characteristics of different orbits (attitude maneuver $\pm 60^\circ$)

Observation capability		Elliptic orbit (km)		Circular orbit (km)		
		250 × 680	250 × 490	490	568	680
Sub-satellite point resolution	Perigee (m)	0.15	0.15	0.3	0.35	0.42
	Apogee (m)	0.28	0.2			
Revisited with a resolution better than 0.2 m	Perigee (d)	7	7	—	—	—
	Apogee (d)	—	—			
Revisited with a resolution better than 0.3 m	Perigee (d)	5	5	Sub-satellite points	—	—
	Apogee (d)	—	Sub-satellite points			
Revisited with a resolution better than 0.5 m	Perigee (d)	5	5	3–4	Daily recursive	1 (daily revisit)
	Apogee (d)	1	3–4			

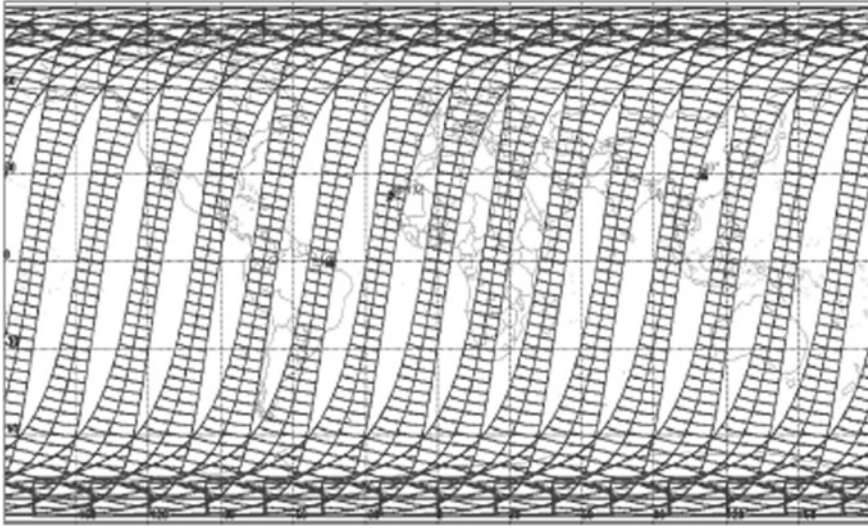


Fig. 2.2 Observation on specific areas by satellite on 568 km daily recursive orbit

2.4 Orbital Analysis and Design of Microwave Imaging Remote Sensing Satellite

2.4.1 Orbit Selection Principle

According to the orbital design requirements and characteristics of high-resolution SAR satellite in Sect. 2.2.2, the orbital type of satellite is determined as the Sun-synchronous, repeat, frozen, dawn–dusk orbit. The orbit parameters shall be comprehensively selected according to the requirements of the mission after the determined type of orbit. The factors for selecting the parameters are summarized as follows:

- (a) **Imaging resolution** of the microwave imaging payload represented by SAR payload is not directly related to the orbit altitude according to the description in Sect. 2.2.2. The optional orbit altitude range of the satellite is obtained under comprehensive consideration with the requirements of the whole satellite power and payload resolution.
- (b) **Imaging swath** of the microwave imaging remote sensing satellite with SAR payload depends on the single-beam width of the payload and the multiple beam-stitching width of the electrical scanning, and has little to do with the orbit altitude, that is, the payload width requirement is not a strong constraint for the selection of the orbit altitude.
- (c) **Coverage and revisit characteristics:** The visible width of the microwave imaging remote sensing satellite with SAR payload depends on the incident angle range of the payload. At present, the incidence angle of most SAR satellites

in the world ranges from 20° to 50° . In addition, the problem of the blind zone of the sub-satellite point exists in SAR payload. When selecting the orbit altitude, the blind zone of the sub-satellite point shall be covered by using the visual range of the adjacent track.

- (d) **Orbital maintenance and maneuverability:** the satellite will consume more fuel by orbit maintenance on lower altitude and orbit maneuver in a wider range. Fuel carrying capacity and fuel consumption in its life cycle of the satellite shall be fully considered.
- (e) **LTDN:** Because the microwave remote sensing satellite has no lighting requirement for the imaging of ground targets, the LTDN at 06:00 or 18:00 is usually selected for them if there is no special requirement.

At present, China's latest civil C band SAR satellite on orbit has the highest resolution of 1 m, and operates in 12 payload modes and 4 polarization modes, representing the highest level of civil SAR satellite in China. This book introduces the design method of the orbits for microwave imaging remote sensing satellite in combination with its typical application.

2.4.2 *Orbital Parameter Determination*

At present, the Sun-synchronous, repeat, frozen, dawn–dusk orbit with LTDN at 06:00 or 18:00 is chosen for most of the global observation of microwave imaging remote sensing satellites. Since the Sun-synchronous orbit is used, once the orbit altitude is determined, the orbital inclination is also fixed. The frozen eccentricity and argument of perigee of the frozen orbit can be determined according to the orbit altitude and inclination. Therefore, for the global observation of microwave imaging remote sensing satellites, the primary task is to determine the orbit altitude.

2.4.2.1 **Orbit Altitude Determination**

For SAR satellites, the selection of orbit altitude shall take the requirements of revisit time, observation coverage, and other mission requirements, as well as the constraints of large-scale systems such as the capability of launch vehicle into account.

- (a) **Launch capability constraint analysis:** CZ-4C Launch Vehicle is selected for the high-resolution microwave imaging remote sensing satellite presented in this book. According to the satellite weight, the launch vehicle can put the satellite into a circular orbit with altitude in the range of 700–750 km.
- (b) **Satellite revisit effectiveness analysis:** According to the mission requirements, the satellite should repeatedly observe 90% of the target area within 1.5 days for an operating mode with a spatial resolution of 10 m and a swath of 100 km. SAR payload shall have the normal incidence angle in the range of 20° – 50° , low scalability of 10° – 20° , and high scalability of 50° – 60° as well as dual-sided view

imaging capability. The mono-track visible range of the satellite has a blind zone within about 10° near the sub-satellite point, which shall be covered by adjacent trajectories. According to the weight of the satellite and the capability of the launch vehicle, revisit cycle analysis and simulation of the orbit with an altitude of about 750 km, it is found that the satellite on the orbit at this altitude meets the mission requirements.

- (c) **Coverage analysis:** According to mission requirements, satellites shall achieve seamless coverage observation on a global scale. The satellites have a variety of imaging modes. The imaging swath of each imaging mode varies from several kilometers to several hundred kilometers. When analyzing the coverage, it is necessary to take into account the coverage under different swaths. The track spacing is designed on the base of the swath of the main imaging mode; for the imaging mode with smaller swath, the image stitching can be achieved by different beam angles of the payload, thus achieving seamless coverage of global areas.

Based on the above three aspects, the Sun-synchronous repeat orbit (altitude: 755.436 3 km, inclination: 98.4110°) of 418 cycles in 29 days meets the mission requirements. The equatorial distance between the adjacent track is 95.9 km, and the operating mode with a swath of 130 and 100 km can be realized to achieve full coverage of the whole world in one repeat period. The latitude range that the sub-satellite point can reach is between 81.589° N and 81.589° S. If the high-scalability mode with an incident angle of 50° – 60° is used, the north and south poles can be fully covered. Therefore, the satellite on the selected Sun-synchronous repeat orbit with running 418 cycles in 29 days has the capability of global ocean monitoring and ice cover observation in the regions of north and south poles.

2.4.2.2 LTDN Determination

SAR payload satellite has no requirement on the lighting condition of the imaging target. Therefore, the LTDN is selected on the base of the satellite itself, but the lighting of the target. If the LTDN of 06:00 or 18:00 is selected, the satellite can continuously receive the sun's lighting without the influence of the umbra, thus reducing the integrate design difficulty of the satellite and energy subsystems.

2.4.2.3 Frozen Orbit Parameter Determination

After the determination of satellite altitude and orbit inclination, the eccentricity and the argument of perigee of frozen orbit can be calculated according to the eccentricity calculation formula of frozen orbit. For the specific eccentricity calculation method, refer to the relevant literature.

2.4.3 Mission Orbit Parameter

Based on the analysis of the previous section, for the typical application selected in this book, the Sun-synchronous orbit with running 418 cycles in 29 days is finally selected for the satellite, its orbit parameters are as follows:

The orbit type: the Sun-synchronous repeat frozen orbit;
 The semimajor axis: 7126.4 km;
 The eccentricity: 0.001;
 The inclination: 98.4° ;
 The argument of perigee: 90° ;
 The LTDN: 06:00 am;
 The period: 99.7 min;
 The number of cycles per day: $14 + 12/29$.

2.4.4 Initial Orbit Offset Design

- (a) **The semimajor axis offset of initial orbit:** The frozen orbit has certain requirements on eccentricity and argument of perigee. Therefore, the negative offset of the semimajor axis of the orbit is reserved for fine-tuning to meet the requirements of the frozen orbit. For the satellite whose attitude maneuverability is limited and the thruster cannot directly provide negative velocity increment, the initial orbit semimajor axis will be offset negatively, while other satellites generally do not consider the initial orbit offset.
- (b) **Orbital inclination offset:** According to the influence of the sun's gravitational perturbation on the inclination of the orbit at different LTDN, the LTDN of the satellite orbit is known as 06:00 am, and the change rate of the orbital inclination caused by the sun's gravitational perturbation is zero, that is, the orbit inclination will not change during the satellite operation process, so the LTDN will remain unchanged. In the nominal case, an initial offset is not required for the initial orbital inclination.

2.4.5 Orbit Control

2.4.5.1 Injection Orbit Adjustment

The microwave remote sensing satellites shall be adjusted for the initial orbit, which is the same as that for the optical remote sensing satellite. For details, please refer to Sect. 2.3.4.

Table 2.9 Theoretical satellite orbit adjustment and orbit control period

$F_{10.7}$	Atmospheric density (kg km^{-3})	Semimajor axis change rate (m d^{-1})	Semimajor axis adjustment (m)	Orbit control frequency (d)
High ($F_{10.7} = 225$)	4.62E-04	-14.20	232.25	16.35
Medium ($F_{10.7} = 150$)	1.13E-05	-0.35	36.36	104.46
Low ($F_{10.7} = 75$)	1.80E-06	-0.06	14.50	261.99

2.4.5.2 Orbit Maintenance

For microwave remote sensing satellites, the task of orbit maintenance for the ground track is to control the ground track within a certain width centered on the nominal position by adjusting the semimajor axis, thus achieving the maintenance of the semimajor axis. The eccentricity and argument of perigee of frozen orbit can be maintained by selecting the phase of orbit maneuver, and vice versa.

For the typical application of this section, the maximum drift range of the satellite ground track ΔL is 4 km, and the ratio of the windward surface area to satellite mass is $0.003 \text{ m}^2/\text{kg}$. Considering the years of different solar activity, the theoretical adjustment and orbit control period of the semimajor axis for ground trajectory orbit maintenance are shown in Table 2.9.

2.4.5.3 Fuel Consumption Analysis for Typical Application of Orbit Control

The fuel consumption for the initial orbit adjustment, orbit maintenance, and attitude control should be considered in the consumption of satellite propellant, whose statistics are shown in Table 2.10. The propellant carried by satellite shall not be at least 98.67 kg, of which a 15% margin shall be left.

Table 2.10 Fuel consumption statistics of microwave remote sensing satellite with SAR payload for typical applications

Items		Analysis results (kg)
Injection orbit adjustment	For semimajor axis	35.70
	For inclination	16.93
Orbit maintenance		3.17
Attitude control		30
Total		85.80

Table 2.11 Revisit and global coverage analysis of satellite in each imaging mode for typical applications in this book

Imaging mode	Resolution (m)	Imaging swath (km)	Average unilateral visual revisit period (d)	Average bilateral visual revisit period (d)	Global coverage time (d)
Bunching mode	1	10	1.5–0.8	0.8–0.4	290
Ultra-fine strip	3	30	1.2–0.7	0.7–0.3	116
Fine strip	5	50	3.4–1.9	1.9–1	58
Standard strip	25	130	3.6–2	2–1	29
Wide scan	100	500	1.3–0.7	0.7–0.4	7
Full polarization	8	30	1.5–0.8	0.8–0.4	116
Wave imaging	10	5	3.4–1.9	1.9–1	580
Global observation imaging	500	650	3.8–2	2–1	7

2.4.6 Observational Capability Analysis

The analysis results of the revisit and global coverage time of satellite in each imaging mode are shown in Table 2.11.

2.4.7 LTDN Drift

For the typical application of the dawn–dusk orbit with LTDN at 06:00 am, the change rate of orbit inclination caused by solar gravitational perturbation is ideally zero, that is, the orbit inclination does not change during satellite operation, so the LTDN will also remain unchanged. However, according to the existing actual TT&C capabilities, the inclination has a TT&C error of 0.01° (including telemetry- and control-error). Considering the inclination TT&C error, the drift of LTDN of the satellite at the nominal launch time is shown in Fig. 2.3.

In nominal LTDN considering the influence of inclination TT&C error, the drift of satellite LTDN during its lifetime ranges from −13.61 min to 13.58 min, and the corresponding range of LTDN is 05:46 am to 06:14 am.

Considering that the zero-window launch may not be possible due to various reasons, if the satellite is launched in advance, the injection LTDN will be earlier, and if the satellite is launched late, the LTDN will be delayed. If the launch window is 0 to +10 min, under the consideration with TT&C error of the 0.01° inclination, the

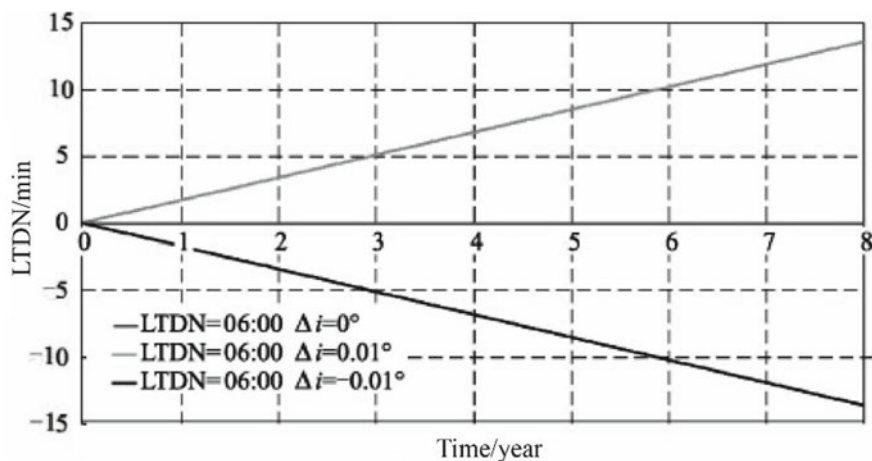


Fig. 2.3 LTDN drift

maximum drift of the satellite LTDN is -25.7 min, and the corresponding LTDN is at 05:34 am. If the requirement of the satellite LTDN range is not met, the satellite's LTDN shall be adjusted by the orbital inclination adjustment during the lifetime to meet the requirement of satellite LTDN range.

This chapter systematically summarizes the recent research achievements on the theoretical research, key technological innovation, and engineering application of remote sensing satellite orbit design. It not only contains various basic knowledge and important theories of satellite orbital mechanics, but also embodies the important application of orbital mechanics in current space mission fronts, thus providing technical support for remote sensing satellites and other current and future major space projects.

Chapter 3

Analysis and Design of High-Resolution Visible Spectral Remote Sensing Satellite System



Abstract As the earliest optical remote sensing satellite, visible spectral remote sensing satellite is of great and profound significance for satellite remote sensing system. High-resolution optical remote sensing satellites have a vast application prospect in mapping, construction, mining, urban planning, land use, resources, management, agricultural investigation, environmental monitoring, emergency relief and geographic information services, and also in military imaging reconnaissance.

3.1 Overview

As the earliest optical remote sensing satellite, visible spectral remote sensing satellite is of great and profound significance for satellite remote sensing system. High-resolution optical remote sensing satellites have a vast application prospect in mapping, construction, mining, urban planning, land use, resources, management, agricultural investigation, environmental monitoring, emergency relief and geographic information services, and also in military imaging reconnaissance. Therefore, countries all over the world attach great importance to the development of high-resolution visible spectral remote sensing satellite system technology, with huge investment.

Based on the overall design experience and application of China's low-orbit high-resolution optical imaging satellite, this chapter focuses on the imaging quality-oriented overall design method of high-resolution visible spectral remote sensing satellite, including the overall design elements, on-orbit dynamic imaging quality design, radiation and geometric calibration, visible spectral remote sensing applications, and other technologies.

3.1.1 Development Overview

At present, representative high-resolution optical remote sensing satellite systems mainly include WorldView, GeoEye, Pleiades, and other commercial satellite series.

Table 3.1 Several advanced high-resolution optical satellites in the world [1, 2]

Satellite name	Country	Launch year	Orbital altitude/km	Sub-satellite point resolution/m	Attitude maneuverability/(°)
GeoEye-1	USA	2008	684	Panchromatic 0.41, multispectral 1.64	±60
WorldView 2	USA	2009	770	Panchromatic 0.46, multispectral 1.84	±45
WorldView 3	USA	2014	617	Panchromatic 0.31, multispectral 1.24	±45
WorldView 4	USA	2016	617	Panchromatic 0.31, multispectral 1.24, short-wave infrared multispectral 3.7	±60
Pleiades-1	France	2011	695	2.0 panchromatic 0.5, multispectral 2.0	±45

Table 3.1 shows the design parameters for several high-resolution optical remote sensing satellite systems.

WorldView and GeoEye satellite series are commercial high-resolution visible remote sensing satellites of the United States, which can provide users with satellite optical remote sensing images with a better resolution than 0.5 m, and have the characteristics of multispectral band and flexible imaging mode.

The French Pleiades satellite series is an agile high-resolution optical remote sensing satellite system that uses super-resolution technology to achieve a ground resolution of 0.5 m visible full-spectral band. Pleiades-1A and Pleiades-1B were launched in 2011 and 2012, respectively.

3.1.2 Trend of Development

- (a) **Ground resolution has been improved continuously:** Ground resolution is a key indicator of optical remote sensing satellite, which determines the application ability of remote sensing satellite. Improving ground resolution will enhance the image interpretation ability of small-size ground targets.
- (b) **The visible-infrared co-aperture integrated design:** enables the optical remote sensing satellite to image in all-day, which can obtain more abundant ground object target radiation characteristic information while improving the satellite’s temporal resolution.

- (c) **Visible-short-wave infrared multispectral Earth observation technology:** The current dominant spectral band configuration mode is the design scheme of visible spectral panchromatic + multispectral bands. The development direction of spectral band configuration is to increase the multispectral bands, especially to expand short-wave multispectral bands. For example, the WorldView-3 satellite is configured with panchromatic +8 visible multispectral +8 short-wave infrared multispectral bands, which greatly enhances the capability of information acquisition and remote sensing applications.
- (d) **High-quality detectors and advanced noise reduction technology:** High-quality visible detectors are the key factors determining the quality of satellite imaging. Using advanced multiplier detectors and backlighting detectors, their advantages of high sensitivity and wide dynamic range can be taken to achieve target detection under the low-light imaging and low-reflectivity conditions. The imaging circuit adopts a special ASIC integrated circuit, which can significantly suppress circuit noise and improve system imaging quality.
- (e) **Developing rapid attitude maneuverability:** High-resolution optical remote sensing satellites widely use Control Moment Gyroscope (CMG) technology with high precision and large momentum to achieve rapid attitude maneuverability.

3.2 Demand Analysis and Technical Characteristics

3.2.1 Demand Analysis

High-resolution visible spectral remote sensing is a core means of space-based fine Earth observation. It is mainly used in urban planning and transportation, disaster prevention and mitigation, environmental monitoring, construction of “The Belt and Road”, national security, and national defense in China.

For urban planning and transportation applications, high-resolution visible satellite remote sensing services provide high-precision remote sensing information for urban planning and refined management, such as dynamic monitoring of urban development and land use, accurate estimation of freight volume and throughput capacity of logistics hub, quantitative evaluation of highway network.

In the application of national disaster prevention and mitigation, high-resolution visible spectral satellite remote sensing image data plays an indispensable role, such as early assessment of disaster risk in geological disaster-prone areas in the disaster prevention stage, remote sensing monitoring and loss assessment of disaster impact scope and physical damage in the disaster relief stage, and guide post-disaster reconstruction planning and recovery work in the post-disaster stage.

In the application of environmental protection monitoring, high-resolution visible spectral satellite data can be used for high-precision verification of pollution sources such as coal-fired power plants in key areas, fine identification of sewage outlets in small rivers, monitoring and evaluation of the safety of drinking water sources,

and remote sensing monitoring of national nature reserves, large-scale projects (such as high-speed rail, nuclear power facilities)/regional development, and construction environment.

In the application of building “Digital Earth”, high-resolution optical satellite remote sensing data is an important basic data guarantee for building advanced “Digital Earth” project, involving big data projects in a series of industries such as “Digital Land”, “Digital Water Conservancy”, “Digital City”, “Digital Agriculture”, “Digital Forestry” and “Digital Environmental Protection”, “Digital Home”, “Digital Campus”, and “Digital life”.

In terms of national security and national defense applications, high-resolution optical remote sensing satellites use their high-resolution advantages to accurately reconnaissance and identify large-scale military targets such as enemy command and control centers, missile bases, navy and air force bases, barracks, warehouses, industrial and transportation facilities, to monitor the deployment and mobilization of their forces, and to identify and confirm nuclear weapons, air defense weapons, aircraft, ships, tanks, and other weapons and equipment.

3.2.2 Technical Characteristics of Visible Spectral Remote Sensing Satellite

The main technical characteristics of high-resolution visible remote sensing satellites include the following:

- (a) **Large-aperture, long-focal-length, and high-resolution optical cameras:** Three-mirror coaxial/off-axis optical system and high-quality Time Delay and Integration CCD (TDI CCD) imaging system are generally used in high-resolution visible spectral remote sensing satellite cameras. The key technologies involved in large-aperture, long-focal-length, and high-resolution optomechanical system mainly include the preparation and processing of large-aperture, high-precision, and high-stability optical element, large-scale and high-stability carbon fiber optomechanical structure, environmental change adaptive optical quantitative compensation system, high-precision stress-free assembly and adjustment, etc.
- (b) **High-speed data processing and transmission technology:** High-resolution visible spectral remote sensing satellite has the characteristics of high image data rate. For sub-meter resolution visible spectral satellites with a swath of more than 10 km, the data rate can reach tens to hundreds of Gb/s, which is a large challenge for on-board data processing capability. Therefore, satellites are usually equipped with high-speed data transmission systems with capabilities of high-speed raw data processing, compression coding, high-speed and large-capacity storage, store and delete simultaneously, high-speed data transmission as well as on-board intelligent processing, to ensure the storage and transmission of massive image data.

- (c) **High-precision, high-stability, high-mobility attitude control technology:** The high-resolution imaging quality places high demands on the attitude measurement, control accuracy, and accuracy of the drift angle compensation of the satellite. The satellite achieves attitude pointing accuracy better than 0.01° (3σ), the attitude stability higher than $5 \times 10^{-4}^\circ/\text{s}$, attitude measurement accuracy of 0.001° (3σ), and the fast attitude maneuverability of $25^\circ/20 \text{ s}$ by equipping with high-precision star tracker, three-float gyro/optical fiber gyroscope, and other attitude measurement sensors, as well as momentum wheel, control moment gyroscope group, and other actuators.
- (d) **Advanced flutter suppression technology:** On-board flutter suppression design is one of the most important parts in the overall design of high-resolution visible spectral remote sensing satellites. In general, the satellite should strictly depend on the imaging quality characteristics and the imaging quality requirements, and put forward clear control requirements for the whole satellite flutter suppression, for example, the requirement of the whole satellite flutter of 50–2000 Hz and the flutter amplitude of less than $7 \times 10^{-3} \text{ mrad}$ are put forward for GeoEye-1; in the general system design, the non-fixed components should be avoided as far as possible, and the flutter characteristics of the on-board flutter source should be strictly controlled and high-level vibration isolation design should be adopted. Flutter suppression characteristics are strictly controlled, and adequate isolation design is adopted. For example, the WorldView-1/2 satellite uses the Solar Array Driving Assembly (SADA) to fully isolate and reduce the vibration of CMG cabin. The on-board flutter characteristics are monitored by equipped high-frequency angular displacement measurement sensor, and the on-board flutter suppression and vibration isolation measures are quantitatively evaluated. For example, GeoEye-1 of the United States and ALOS of Japan are equipped with high-precision high-frequency angular displacement sensors, so as to realize the measurement, quantitative analysis, and on-board flutter suppression.
- (e) **High-precision image positioning technology:** High-resolution visible spectral remote sensing satellite improves the geometric positioning accuracy of remote sensing image through the integrated design of high-resolution optical camera, high-precision star tracker, and gyroscope. For example, GeoEye-1 adopts a high-precision star tracker design, which achieves high geometric positioning accuracy with plane positioning accuracy better than 4 m (CE90) and elevation accuracy better than 6 m (LE90).

3.3 Key Performance Indicators of Imaging Quality of Visible Spectral Remote Sensing System

The quality of visible spectral satellite imaging includes image radiation quality and image geometric quality, which are constrained and evaluated objectively by corresponding technical indicators. In order to ensure the imaging quality of the

whole satellite, the integrity of the relevant indicators for evaluating satellite imaging quality must be ensured first. In addition, due to long satellite imaging links and many and complex parts affecting imaging quality, the correlation between objective indicators and imaging quality must be comprehensively analyzed.

3.3.1 *Radiation Imaging Quality*

Radiation imaging quality refers to the ability of remote sensing images generated by imaging systems for reflecting the energy distribution of the surface. There are many evaluation indicators for the quality of radiation imaging, among which the on-orbit dynamic Modulation Transfer Function (MTF), Signal-to-Noise Ratio (SNR), and the dynamic range are the core indicators for evaluating the quality of satellite radiation imaging, which can not only quantitatively reflect the impact of each part in the imaging link on the imaging quality, but also guide the engineering design and manufacture of satellite and remote sensing cameras.

- (a) **On-orbit dynamic MTF** as a linear system, the MTF of the visible spectral remote sensing satellite is a function of the ratio of image modulation degree to target modulation degree. This function represents the transmission capability of satellite for target contrast at different spatial frequencies, which mainly affects the sharpness of remote sensing images. The main factors affecting MTF include atmospheric conditions, camera performance, satellite on-orbit control accuracy and micro-vibration characteristics, and integration time control accuracy.
- (b) **On-orbit SNR** of visible spectral remote sensing satellite refers to the ratio of signal to noise of the satellite output image, and is an important parameter to characterize the radiation characteristics of visible spectral remote sensing satellite. The SNR is related to both noise level and signal level. The signal strength is mainly determined by the design of the photoelectric imaging system and the input imaging conditions. The noise level depends on the detector noise and the noise characteristics of the imaging circuit.
- (c) **On-orbit dynamic range**: on-orbit dynamic range refers to the maximum and minimum input signal range that visible remote sensing satellites can adapt when the satellite is on-orbit. It describes the adaptability of visible remote sensing satellites to input illumination and signal conditions. The main factors affecting on-orbit dynamic range include external imaging conditions, detector characteristics, noise characteristics of imaging circuit, and setting of imaging parameters.

3.3.2 *Geometric Imaging Quality*

Geometric imaging quality refers to the ability of remote sensing images generated by the imaging system to accurately describe the geometry and position accuracy

of the target. The evaluation indexes of image geometric quality mainly include: resolution of ground pixels, imaging width, geometric positioning accuracy, image distortion, and spectral registration accuracy, among which geometric positioning accuracy is the main factor of evaluating the geometric quality of satellite images. Therefore, it is necessary to go deep into the evaluation of the key factors in the satellite design scheme and design parameters, and to take corresponding assurance measures.

- (a) **Ground Sampling Distance (GSD):** For TDI CCD camera, the ground sampling distance is characterized by the minimum ground size corresponding to the detector unit. The main influencing factors include orbital altitude, camera focal length, pixel size, etc.
- (b) **Imaging width:** The imaging width refers to the ground width observed by one orbit pass in the direction perpendicular to visible spectral remote sensing satellite's flight ground trajectory. Factors affecting it include camera field of view, orbital altitude, etc.
- (c) **Geometric positioning accuracy:** Geometric positioning accuracy refers to the geometric positioning accuracy of remote sensing imaging system pointing to the ground at a certain time by means of orbit determination and attitude determination by the satellite itself. It is an important index reflecting the ability of satellite plane and stereo mapping. The main factors affecting the accuracy of geometric positioning include the Internal Orientation Parameter (IOP) error (principal point, principal distance, and distortion calibration error) and the External Orientation Parameter (EOP) error (satellite-sensitive accuracy and attitude measurement error, satellite stability, camera and satellite-sensitive installation error, orbit determination accuracy, etc.).
- (d) **Image distortion:** The optical system of the visible spectral remote sensing satellite is not an ideal optical system, so the magnification of the image varies with the different field of view, which makes the geometric figure of the image different from the real geometric figure of the object in the selected projection. This kind of distortion is called image distortion. Image distortion can be measured by laboratory precision angle measurement method, and can be calibrated on-orbit. However, due to the influence of the on-orbit space environment, there will be some random changes. Image distortion is mainly affected by camera optical system distortion, satellite attitude stability, structure, and thermal stability.
- (e) **Spectral registration accuracy:** For remote sensing satellites with multiple imaging spectral bands, the information of each spectral band shall be fused to obtain richer landmark information. The registration error between the image data of each spectral band is the accuracy of spectral band registration. The accuracy of spectral registration is mainly affected by the manufacturing and installation accuracy of the detector, the distortion of the optical system, and the attitude jitter of the satellite.

3.4 Analysis and Design of Imaging Quality of High-Resolution Visible Spectral Camera

3.4.1 Overview of the Development of High-Resolution Visible Spectral Cameras

Visible spectral remote sensing satellite cameras all over the world have gradually developed by mainly improving the GSD index, which put forward a high demand on aperture, focal length, detector size, and responsiveness of optical system. The main indicators of prevailing high-resolution optical remote sensing cameras are shown in Table 3.2.

The development of high-resolution visible spectral cameras has the following characteristics.

3.4.1.1 Camera Parameter Optimization Based on Imaging Quality Design

From the initial single-line array, the CCD has gradually developed into a TDI CCD, and further into a back-illuminated TDI CCD, of which the photoelectric conversion efficiency and energy acquisition capability of the detector and the comprehensive detection performance have been significantly improved. At present, TDI CCD imaging system is widely used in the internationally popular high-resolution visible spectral remote sensing cameras, which significantly increases the energy obtained by the camera detector exposure, and lays a technical foundation for the design and application of large F -number (i.e., the ratio of the camera focal length to optical aperture), that is, high-performance TDI CCD detector is used to compensate the lack of exposure energy of large F -number cameras. As can be seen from Table 3.2, the detector of Pleiades is back-illuminated TDI CCD with the largest F -number and the largest detector pixel size; the detector of WorldView and GeoEye series satellite is also back-illuminated TDI CCD but with smaller pixel size. Their common design features are as follows: as one of the main design basis, the $\lambda F/p$ (ratio of optical sampling frequency to detector sampling frequency) is designed close to 1, where λ is the wavelength, F is the F -number of camera (i.e., ratio of camera focal length to optical aperture), and P is the pixel size of the detector.

3.4.1.2 High-Resolution Visible Spectral/Short-Wave Infrared Spectroscopy

Multispectral detection design is often used in cameras to improve the information acquisition ability of optical remote sensing satellites. In addition to the visible full-spectrum, it is also matched with multispectral bands, and the more commonly

Table 3.2 Design of parameter of high-resolution optical remote sensing satellite camera in the world (assume λ to be 0.65 μm) [1, 2]

Satellite	Mass/kg	Width/km	Aperture/m	Focal length/m	F number	Detector type	Pixel size/ μm	$\lambda F/p$
Pleiades	195	20	0.65	12.9	19.8	back-illuminated TDI CCD	13×13	0.99
GeoEye-1	450	15.3	1.1	13.3	12.1	back-illuminated TDI CCD	8×8	0.986
WorldView-2	680	16.4	1.1	13.3	12.1	back-illuminated TDI CCD	8×8	0.98
WorldView-3	—	13.1	1.1	15.9	14.5	back-illuminated TDI CCD	8×8	1.176

used is the four-band multispectral band. At present, the full chromatographic band with a visible-shortwave infrared multispectral band is newly developed, and the visible-near-infrared-shortwave infrared co-aperture integrated design is applied.

3.4.1.3 Lightweight Technology of Optomechanical Structure

In the three-mirror optical system used in the high-resolution visible spectral camera, the main optical elements are composed of mirrors. Mirror is one of the main components of space optical remote sensing systems. In general, the mass of the instrument is approximately proportional to the 2.4th power of the primary mirror aperture, and the ratio of the mirror mass to that of the supporting structure is 10–20. In order to reduce the mass of the mirror, the machined honeycomb or sandwich honeycomb structure is usually used for the back of the mirror, which can effectively reduce the mass of the large mirror by more than 65%. High stability and high specific stiffness materials are often used in optomechanical structures. Large-scale mirror can be made of SiC, glass with Ultra-Low Expansion (ULE), etc. The structural parts are made of composite materials based on ferroalloy or carbon fiber. These materials have the characteristics of lightweight, high specific stiffness, and small expansion coefficient, which can achieve lightweight of high-resolution camera optomechanical structures.

3.4.1.4 Integrated Design of Satellite Platform-Payload

Because the size and weight of high-resolution optical cameras are very large, in order to obtain better camera imaging quality, the camera and satellite platform shall be designed in an integrated manner, including the integrated optical, mechanical, electrical, and thermal design with high precision and high stability, the integrated installation of camera, high-precision star tracker, and gyroscope as well as its high-precision thermal control equipment, thus improving the stability of the angle between the optical axis on orbit and the geometric positioning accuracy of the imaging.

3.4.2 Key Design Elements of Visible Spectral Camera

The main technical indicators of optical camera can directly affect the quality of remote sensing image data. The key design elements affecting the image quality shall be fully identified, optimized, and controlled in the design and development of cameras. The main design elements include camera focal length, camera field of view, spectral band configuration, selection of detector, camera aperture, camera optical system design, stray light suppression design, optical system distortion, valid

pixel number, focal plane detector stitching, imaging circuit design, focusing system design, thermo-optical stability design, mechanical stability design, etc.

3.4.3 Design of GSD and Camera Focal Length

Push-broom imaging system is usually used by high-resolution visible spectral cameras. The GSD of the camera is related to the focal length of the camera, the pixel size of the detector, the altitude of the satellite orbit, and the yaw angle. When imaging at the sub-satellite point, the GSD in the flight direction of the satellite and the direction of the line array are the same, which is determined by

$$\text{GSD} = \frac{p}{f} \times H \quad (3.1)$$

where GSD is the Ground Sampling Distance, p is the pixel size, f is the camera focal length, and H is the orbital altitude. For example, for a 500 km orbital altitude, if a GSD better than 0.5 m is achieved by using a detector with a pixel size of $10 \mu\text{m} \times 10 \mu\text{m}$, the focal length should be no less than 10 m.

3.4.4 Image Width and Camera FOV Design

Camera FOV depends on imaging swath and distance. In the case of satellite push-broom imaging at sub-satellite point, the relationship between coverage swath and camera FOV and satellite orbital altitude is as follows:

$$S = 2H \times \tan(\omega), \quad (3.2)$$

where S is the coverage swath, H is the orbital altitude, and ω is the half FOV of the camera. For example, for 500 km orbital altitude, in order to achieve a swath of not less than 30 km, the effective FOV of the camera should not be less than 3.45° .

3.4.5 Spectral Band Configuration

For high-resolution optical remote sensing satellites, the spectral band range of camera imaging is a very important performance index. The selection, realization, and calibration of spectral band spans the whole process of the visible camera from demonstration, development to on-orbit application. The band selection of high-resolution visible camera is generally in the range of visible to near-infrared (0.4–1.5 μm). A panchromatic spectral band and several multispectral bands are selected.

Table 3.3 Spectral band configuration of typical high-resolution visible spectral satellites in the world [1, 2]

Satellite	Panchromatic	Multispectral	
	Spectral range/ μm	Number of spectral bands	Spectral range/ μm
Pleiades 1	0.48 ~ 0.83	4	Blue 0.43 ~ 0.55; green 0.49 ~ 0.61; red 0.60 ~ 0.72; NIR 0.75 ~ 0.95
GeoEye-1	0.45 ~ 0.80	4	Blue 0.45 ~ 0.52; green 0.52 ~ 0.60; red 0.625 ~ 0.695; NIR 0.76 ~ 0.90
WorldView-2	0.45 ~ 0.80	8	Purple 0.40 ~ 0.45; blue 0.45 ~ 0.51; green 0.51 ~ 0.58; yellow 0.585 ~ 0.625; Red 0.60 ~ 0.69; red edge 0.705 ~ 0.745; NIR 0.77 ~ 0.895; NIR 0.86 ~ 1.04
WorldView-3	0.45 ~ 0.80	16	Coastal blue 0.400 ~ 0.452; blue 0.448 ~ 0.510; green 0.518 ~ 0.586; yellow 0.590 ~ 0.630; red 0.632 ~ 0.692; red edge 0.706 ~ 0.746; NIR 1.772 ~ 1.890; NIR 2.866 ~ 2.954; SWIR 1.195 ~ 1.225; SWIR 1.55 ~ 1.59; SWIR 1.640 ~ 1.680; SWIR 1.71 ~ 1.75; SWIR 2.145 ~ 2.185; SWIR 2.185 ~ 2.225; SWIR 2.235 ~ 2.285; SWIR 2.295 ~ 2.365
GF-2	0.45 ~ 0.90	4	Blue 0.45 ~ 0.52; green 0.52 ~ 0.59; red 0.63 ~ 0.69; NIR 0.77 ~ 0.89

The band selection of typical high-resolution remote sensing satellites is shown in Table 3.3.

3.4.5.1 Selection of Panchromatic Spectral Band

High-resolution visible spectral remote sensing satellite with a panchromatic spectral band can make full use of the spectral response characteristics of TDI CCD detector (that is, the response peak is near 0.7–0.8 μm) to achieve high-resolution imaging, and provide high-resolution remote sensing image and high-precision geometric characteristics.

From the perspective of panchromatic spectral band range selection of typical optical remote sensing satellite cameras, the early visible satellites use 0.4–0.8 μm

band range, while the WorldView-2 and GeoEye-1 satellites select 0.45–0.9 μm band range and Pleiades satellites select a band range of 0.48–0.83 μm . These band ranges implement the requirements of visible spectral observation. Note that the reflection characteristics of some typical military targets are more obvious in the near-infrared band. The extension of the panchromatic spectral band to the near-infrared band is more conducive to the application of high-resolution reconnaissance and remote sensing. In the 0.8–0.9 μm near-infrared spectral band, the gray level of the vegetation is consistent with that of the building area. Therefore, in the process of panchromatic–multispectral fusion, the near-infrared spectral band is cut off to obtain a fusion influence close to the true color. The panchromatic spectral band is selected according to the actual application.

3.4.5.2 Selection of Multispectral Bands

Configuration of multispectral bands can reveal the spectral characteristics and physical details of the object surface, and image data fusion and inversion can enhance the resolution ability of remote sensing image features. The fusion of multispectral and panchromatic images has richer information, which is more conducive to visual interpretation and classification of object attributes, thus promoting the fine application of high-resolution remote sensing.

At present, panchromatic spectral band and multispectral bands are used in all visible remote sensing satellites. The ratio of panchromatic ground pixels resolution to multispectral ground pixels resolution is generally 1:4. The common multispectral bands of satellites are usually 0.45–0.52, 0.52–0.60, 0.63–0.69, 0.76–0.90, etc.

3.4.6 Selection of Detector

Camera detector is the core component of the camera, and its performance bears directly on the image quality of the camera. In order to ensure high imaging quality, TDI CCD with time delay integration function is widely used, which can effectively improve the electromagnetic radiation energy and dynamic range of a ground object obtained by the visible spectral camera, and on-orbit imaging quality. The advantages of TDI CCD detector are mainly embodied in the following aspects:

- (1) In the push-broom imaging process, multiline detectors expose the same scene for several times, and increase exposure time by m factors (m is the integral number: such as 12, 24, 32, 48, 64, 96), signal energy also increases m times, and device noise increases about $\sqrt{m}$ times, thus improving the SNR of imaging.
- (2) The dynamic range of camera imaging is improved significantly, especially the imaging performance under low illumination.

- (3) For visible spectral cameras with high-resolution and long-focal-length, create conditions for the application of optical systems with small relative aperture (large F -number), which can greatly reduce the size and weight of the camera.

For a TMA optical camera with a large-aperture, non-obscuraton field of view, and high modulation transfer function, TDI detectors with relatively small pixel sizes can be selected. Its main parameters include the following:

- (1) **Line Pixel Number** mainly affects the number of detector splices needed to achieve valid pixel number index and width index, and at the same time restricts the interface design between camera and data transmission system.
- (2) **Pixel size** mainly affects the resolution of the ground pixels that the camera can achieve at a certain orbital altitude.
- (3) **Integral grade** in many stages can be generally selected for on-orbit dynamic. By optimizing the integral grade settings of TDI CCD, better image SNR and dynamic range can be obtained for different objects and illumination conditions.
- (4) **Spectral range** of each spectral band collecting optical signal has a great influence on image application.
- (5) **Line rate** is related to the imaging line frequency, which further affects the highest achievable resolution of the camera at a certain orbital altitude;
- (6) **Charge conversion efficiency** is one of the most important parameters that directly affects the performance of the camera such as SNR in the application of CCD. It represents the optical energy input on each pixel, which is related to the photoelectric conversion efficiency.

The main parameters of several typical TDI CCD devices are given in Table 3.4.

Table 3.4 Main parameters of TDI CCD devices

Parameter	Model	
	TDI CCD detector1	TDI CCD detector2
Line pixel number	Panchromatic 6.144, multispectral 1.536/mono-spectral band	Panchromatic 4.096, multispectral 1.024/mono-spectral band
Pixel size/ μm	Panchromatic 7, multispectral 28	Panchromatic 8.75, multispectral 35
Maximum line rate/kHz	30.9, multispectral 15.73	80, multispectral 20
Saturated output/mV	2.000	Panchromatic 1.380, multispectral 2.100
Conversion efficiency/ $(\mu\text{V} \bullet \text{e}^{-1})$	Panchromatic 12, multispectral 5	Panchromatic 11.5, multispectral 3.5
Equivalent noise/ μV (rms)	Panchromatic 550, multispectral 450	Panchromatic 460, multispectral 350

3.4.7 Selection of Relative Aperture of Lens and Determination of Camera Aperture

The relative aperture of the lens may affect the ability of light energy acquisition (SNR) and resolution (modulation transfer function), as well as the size of the camera, the optical system, and the complexity of the whole camera. Because the mass of the camera is approximately proportional to the square of the relative aperture (F -number), the optimal design of relative aperture can reduce the size and weight of the camera on the premise of ensuring the imaging quality.

3.4.7.1 Relationship Between Aperture and Resolution of Ground Pixels

The ultimate resolution of the optical system is equal to the radius of the Elliptic Spot $1.22\lambda/D$, where λ is the central wavelength of the spectral band and D is the optical aperture of the optical system. Equation (3.3) should be satisfied in selecting the aperture of the optical system:

$$\text{GSD}/H > 0.61\lambda/D, \quad (3.3)$$

where GSD is Ground Sampling Distance and H is orbital altitude.

3.4.7.2 Relative Aperture and Optical System MTF

The relationship between MTF and aperture of the optical system is as follows:

$$\text{MTF} = \frac{2}{\pi} \left[\cos^{-1} \left(\frac{v}{v_{\text{oc}}} \right) - \frac{v}{v_{\text{oc}}} \sqrt{1 - \left(\frac{v}{v_{\text{oc}}} \right)^2} \right], \quad (3.4)$$

where v is Nyquist frequency, v_{oc} is optical space cutoff frequency, $v_{\text{oc}} = D/(\lambda f')$, λ is average wavelength (assuming $\lambda = 0.65 \mu\text{m}$), f' is camera focal length. For example, if $\text{MTF}_{\text{optics}}$ of the camera optical system is ≥ 0.45 , and considering the aberration and obscuration of the actual optical system, the F -number range of the camera can be calculated to be ≤ 12 .

3.4.7.3 SNR and Relative Aperture of Camera

$$\text{SNR} = \frac{m \cdot t \cdot \frac{\pi}{4} \cdot \left(\frac{D}{f} \right)^2 \cdot (1 - \beta) \cdot T_e \cdot \int_{\lambda_1}^{\lambda_2} L_p(\lambda) \cdot R(\lambda) \cdot d\lambda}{\text{Noise}}, \quad (3.5)$$

where m is the optional integral grade of the CCD, t is the exposure time during one integration, $\frac{D}{f}$ represents the relative aperture of the optical system, β is the surface obscuration coefficient of the camera, and T_e is the equivalent spectral transmittance of the optical system, $L_P(\lambda)$ is the spectral radiance before the entrance pupil, $R(\lambda)$ is the normalized spectral responsivity of the CCD. Generally, after the relevant design parameters of the camera are determined, the calculation of the modulation transfer function and the SNR is performed to check whether the selected F -number can satisfy the performance requirement of the camera.

3.4.8 Design of Camera Optical System

3.4.8.1 Selection of Optical Systems

At present, the optical systems of remote sensing satellite cameras are mainly refractive and reflective optical systems. Optical system selection should be based on the requirements of GSD, optical modulation transfer function, width, dimension, and weight. For high-resolution and long focal length visible spectral cameras, especially those with a focal length of more than 5 m, the refractive optical system is difficult to achieve due to the limitation of the size and weight of satellite platform. At present, most high-resolution optical remote sensing satellites adopt the TMA system, whose main advantages are that it can better eliminate astigmatism and field curvature, so as to achieve high image quality and increase the effective field of view; and the optical system structure is compact, which greatly reduces the size of the camera system.

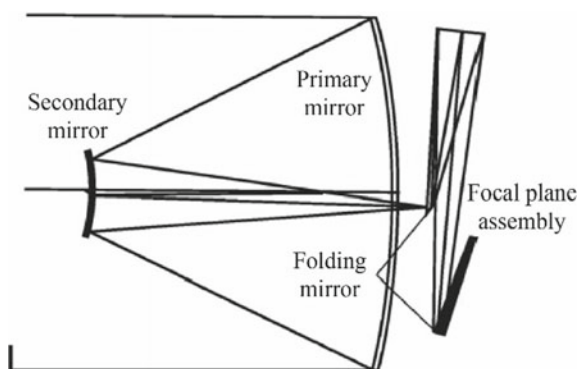
The TMA optical system is divided into the coaxial TMA and the off-axis TMA, which have respective advantages and characteristics. In the selection, in-depth argumentation, analysis, and preferred selection should be carried out for different tasks and different application requirements.

(1) Coaxial TMA optical system

Coaxial TMA optical system adopts coaxial mode. In addition to primary, secondary, and triple mirrors, a planar mirror is usually used for refracting optical path. The optical path diagram of a coaxial three-mirror optical system is shown in Fig. 3.1.

The typical representatives of coaxial TMA optical system are the cameras of United States GeoEye-1, WorldView-2/3/4, French Pleiades, and other high-resolution remote sensing satellites. Compared with the off-axis TMA optical system, the main advantages of the coaxial TMA optical system include compact structure, good thermal stability, and axisymmetric characteristics with less inertia, which can be apt to realize fast attitude maneuverability of satellite on orbit. Its disadvantage is that central obscuration reduces the energy of entrance pupil, which has a negative impact on imaging quality.

Fig. 3.1 Optical path diagram of coaxial TMA optical system



(2) Off-axis TMA optical system

In order to improve the ability of receiving light energy and the image quality of the off-axis field of view, an off-axis TMA optical system without central obscuration has been developed step by step. The off-axis TMA system without obscuration has two main structures: one is a secondary imaging optical system, as shown in Fig. 3.2, in which the first image is shot by the primary mirror or the primary mirror and the secondary mirror, and then this image is captured on the focal plane by the latter system. This method is beneficial to eliminate the stray light design, but cannot achieve a larger field of view. Another method is a primary imaging optical system without the intermediate imaging. As shown in Fig. 3.3, it can achieve a larger field of view. At present, the off-axis TMA optical system usually has a larger field of view in the swath direction and a smaller field of view in the flight direction, so the line array imaging detector is adopted as a focal plane detector.

The typical off-axis TMA optical system is the optical system of QuickBird-2, WorldView-1 satellite camera in the United States. The main advantages of off-axis TMA optical system are large field of view angle and high modulation function of

Fig. 3.2 TMA system with intermediate imaging

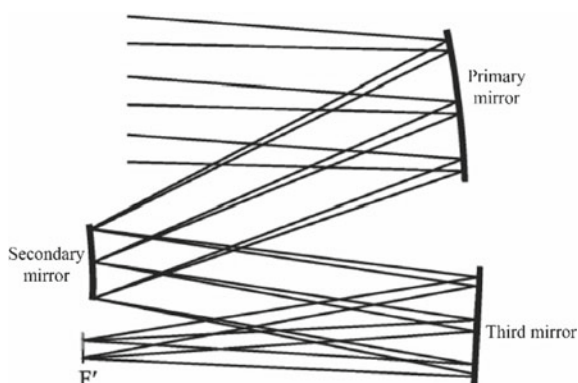
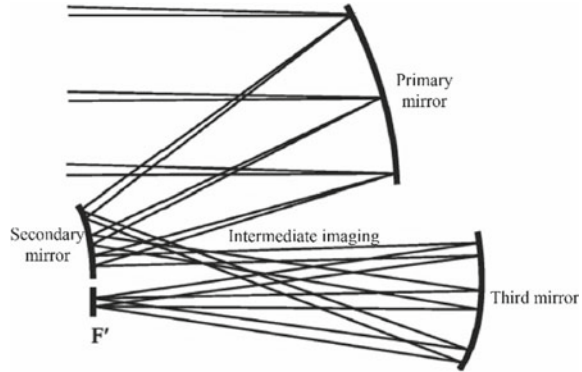


Fig. 3.3 TMA system without intermediate imaging



optical system, but it is difficult to process, assembly and adjust, and the distortion of field of view edge is large.

3.4.8.2 Design of Optical System

The GSD of the high-resolution visible spectral camera is limited by the diffraction limit of optical system. The diameter of the Airy spot in the optical system is

$$d_{\text{Airy}} = 2.44\lambda F. \quad (3.6)$$

According to the sampling principle, in order to fully sample the optical signal on the focal plane of the detector, the diameter of the Airy spot in the optical system should be larger than or equal to the size of two pixels of the detector. Based on Rayleigh's condition, when the minimum and maximum values of the two image illuminance synthesis curves differ by 26%, the two points are regarded to be distinguishable. According to the sampling principle and Rayleigh condition, the design requirements of Eq. (3.7) can be obtained.

$$1.845\lambda F \geq 2p \quad (3.7)$$

$$\frac{\lambda F}{p} \geq 0.9225 \quad (3.8)$$

The parameter matching between the detector and the optical system is to be taken into account comprehensively in the design of the camera optical system, and the design optimization shall be carried out to reduce the aliasing influence caused by spatial sampling. The normalized frequency γ of the camera is defined as

$$\gamma = \frac{v}{v_c} = \frac{1/(2p)}{1/(\lambda F)} = \frac{\lambda F}{2p}, \quad (3.9)$$

where ν is the Nyquist frequency of the detector, ν_c is the cutoff space frequency of the lens, λ is the central wavelength of the operating spectral band, and F is the reciprocal of the relative aperture of the optical system.

- (1) If $\nu < \frac{1}{2}\nu_c$, $\frac{\lambda F}{p} < 1$, the spatial resolution of the camera system is determined by the sampling frequency of the detector, the optical system is under-sampling, and the information of the optical system is lost to some extent in the process of sampling and restoration. In the process of restoration, the high-frequency information component of the image will be missing, resulting in blurred image details;
- (2) If $\nu = \frac{1}{2}\nu_c$, $\frac{\lambda F}{p} = 1$, the diffraction limit of the optical system is equal to the sampling frequency of the detector, and the Nyquist frequency of the camera is half of the cutoff frequency of the optical system, and there is aliasing of high-frequency components;
- (3) If $\frac{1}{2}\nu_c < \nu < \nu_c$, $1 < \frac{\lambda F}{p} < 2$, the spatial resolution of the camera system is dependent upon the detector, the optical system is under-sampling, and the image details can be partially restored;
- (4) If $\nu = \nu_c$, $\frac{\lambda F}{p} = 2$, the resolution of the camera system is dependent on the diffraction limit of the optical system, the camera system is oversampling and the spectrum is not aliased.

The parameter matching between detector and optical system shall be taken into account in the design of a camera optical system, and the design optimization shall be carried out to reduce the aliasing influence caused by spatial sampling. In recent years, with the application of backlighting TDI CCD and the technological progress of high-speed and low-noise imaging circuit, under the premise of ensuring the imaging quality of the system corresponding to the application requirements, the large F -number camera system was designed by using the system optimization design idea with $\frac{\lambda F}{p}$ close to 1. For example, GeoEye and WorldView series satellites all realize the design of large F -number and small pixel system, whose $\frac{\lambda F}{p}$ is close to 1. Under the same pupil diameter, the focal length and Instantaneous Field Of View (IFOV) of the system and the resolution of the ground pixel are effectively improved, and the size and weight of the camera system is reduced.

For a visible spectral camera with a focal length of 10 m, an imaging detector pixel size of 10 μm , and a F -number of 12, after optimized design with a system-wide matching, its average full field of the camera optical system at Nyquist frequency reaches $\text{MTF}_{\text{optical system}} = 0.45$ according to Eq. (3.4).

3.4.8.3 Processing, Assembly, and Adjustment Technology of the Optical System

Because the modulation transfer function of the large optical system is very sensitive to surface processing accuracy and assembly and adjustment error of optical system, in order to ensure the design goal of the modulation transfer function of optical

system and reduce the loss in optical processing and assembly process, the main measures taken include the following:

- (a) improving the processing accuracy of large-aperture aspherical surface in the optical surface processing;
- (b) adopting the unloading design with stress and thermal deformation for both the mirror assembly and the main bearing structure to achieve stress-free installation;
- (c) strictly controlling temperature, airflow, and micro-vibration from the environment to minimize environmental stress in the process of assembly and adjustment; and
- (d) carrying out multidirectional gravity impact test, modulation transfer function restorability test in microgravity, and gravity compensation strategy.

Based on the engineering experience, the processing, assembly, and adjustment factor of a high-resolution visible spectral camera lens is generally $MTF_{\text{lens processing}} = 0.85\text{--}0.90$.

3.4.9 Design for Stray Radiation Suppression

The diaphragm is the key device to suppress the stray light and ensure the image quality of the camera. It is of great significance to improve the contrast and SNR of on-orbit imaging. The sources of stray light in the optical system mainly include: stray light out of the field of view, which is reflected to the image plane by the third mirror without passing through the primary mirror or secondary mirror; the beam in the field of view, which is nonimaging light, reflected to the image plane many times through the mirror and not passing through the imaging light path; stray light, which lights out of the field of view and is diffusely reflected to the image plane by the surface of the lens barrel and other structural parts.

In the design of the optomechanical structure, the system design of eliminating the stray light should be carried out for the above stray light source, so as to minimize the stray light entering the image plane. The stray light suppression methods in camera optical system mainly include that the influence of primary stray light should be considered in the selection of optical system and the design of parameters to achieve the complete suppression of primary stray light; the secondary stray light is suppressed by reducing the roughness of the mirror surface in the optical path, which should be controlled within 3 nm; and apply ultralow reflectivity coating and built-in light-blocking structure on the inner wall of the optical lens to suppress the third stray light.

Specialized simulation software, such as TracePro, is used to analyze the influence of incident stray light at different angles in order to determine the influence of stray light suppression. Point Source Transmittance (PST), the ratio of the light energy reaching the image plane to the light energy of the input aperture perpendicular to the incident direction of light, is used as a measure to evaluate the influence of stray

light. The calculated data are the optical power density of the image plane in the case where the incident light power density is 1 W/cm^2 . The average PST of each off-axis angle of the optical system at each field of view is regarded as the final PST value of the system.

The relationship between the stray light coefficient V and the MTF is

$$\text{MTF}_{\text{stay light}} = \frac{1}{1 + V} \quad (3.10)$$

In general, the stray suppression coefficient of the optical system should be controlled below 3%, i.e., $V = 3\%$. The loss of MTF due to stray light is 0.97.

3.4.10 Optical System Distortion Control and Analysis

In the optical design of the high-resolution visible spectral camera, it is generally required that the distortion in the effective field of view to be $\leq 1.5\%$. After the assembling and adjusting of the camera optical system, the camera distortion should be tested, calibrated, and the distortion variables are to be controlled. In order to improve the geometric positioning accuracy of satellite images, it is necessary to adopt high-precision temperature control to ensure the stability of the on-orbit distortion of camera. The orientation of each pixel is accurately calibrated on orbit by using the high-precision calibration field on ground to ensure high geometric accuracy of the image.

3.4.11 Determination of the Number of Valid Pixels

The valid pixel number of the visible spectral camera is determined by the swath of the sub-satellite point and the resolution of the camera. At present, the number of pixels integrated into a single detector is very limited by the actual technical level. For this reason, multiple detector stitching methods are usually used to fill the effective field of view of the camera. For example, the pixel number of a single TDI CCD detector is 6144 for panchromatic/1536 for multispectral pixels. If the camera imaging resolution is 0.5 m and the swath is 30 km, the panchromatic image requires 60,000 valid pixels, the four-band multispectral image requires $4 \times 15,000$ valid pixels, and the total number of detector chips is $60,000/6144 \approx 9.7$.

3.4.12 Focal Plane Detector Stitching and Stitching Accuracy

3.4.12.1 Stitching of Focal Plane Detectors

Stitching methods of focal plane detectors include mechanical stitching, FOV stitching, optical stitching, and mirror stitching.

(a) Mechanical stitching

Mechanical stitching, also known as chip stitching, is to bond the front and back ends of several detector chips to form a long line array on a transparent focal plane substrate. The advantage of this method is that the imaging relationship is simple and complete, and there is no circuit or optical complexity caused by field of view stitching and optical stitching. However, this method also has some drawbacks. For example, due to the limitation of process structure, there will be 2–3 pixel-sized non-photo sensitive pixels in the splicing between the two chips, which results in image defects.

(b) FOV (Field of View) stitching

FOV stitching is to arrange several detectors in two rows and mount them on the focal plane substrate in a step form, as shown in Fig. 3.4. Two rows of detectors do not image the target at the same time, relative to the image of the first row, the second row has a relatively large delay.

When the camera is imaging on orbit, the optical system of the camera itself has a distortion problem. The orientation of the line array of the detector scan should not be kept perpendicular to the satellite flight direction because of the installation orientation error of the camera on the satellite, as well as the attitude control error of the satellite and the Earth rotation rate. Thus the position projection of the front line array on the second array is changed compared to the ideal situation, then pixel gaps or overlaps may occur, resulting in “image gaps” when the individual detector images are stitched under some imaging conditions. In order to avoid the “gaps” of image stitching, the minimum number of overlapping pixels between two adjacent detectors is

$$N = \frac{D \tan \theta}{d}. \quad (3.11)$$

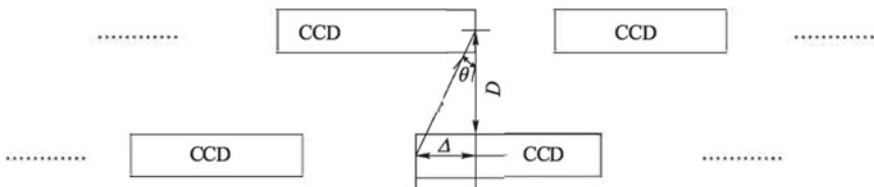


Fig. 3.4 Schematic diagram of overlapping pixels in FOV stitching

where D is the distance between two line arrays of detectors, d is the detector pixel size, and θ is the maximum error angle, at which the estimated line array is not perpendicular to the direction of flight.

For cameras with a pixel size of $10\text{ }\mu\text{m}$, a spacing of 46.6 mm between two rows of detectors, the field of view of 3.5° as well as a field of view distortion of no more than 1.5% , when the maximum error angle between the predicted line array and the flight direction is 0.05° , the number of overlapping pixels needed of two adjacent CCDs is not less than 5 pixels according to the formula. The distortion of the optical system varies with the field of view, so the demand of overlapping pixels for each detector should be calculated separately according to its position in the field of view. In addition, considering the requirements of width and design margin, the number of stitched pixels can be increased when the number of valid pixels is allowed.

(c) Optical stitching

Optical stitching refers to the installation of detectors on both sides of a cubic prism coated with a reflective film on a 45° inclined plane. The focal plane detector forms a continuous long line array when viewed from the entrance surface of the cubic prism anchor. Optical stitching methods include semi-reflection and semi-transmission, and total reflection and total transmission.

Semi-reflection and semi-transmission method is to coat all the cubic prisms, and the reflectivity and transmittance are equal, which are close to 50% . In optical stitching, the initial pixels of the latter detector are arranged next to the last pixels of the migrating device, and all the pixels are utilized, but the light energy entering the camera is lost by more than half, so this stitching method is seldom used at present.

Total reflection and total transmission method is to coat the total reflection film on the inclined surface corresponding to the reflected light and not on the inclined surface corresponding to the transmitted light. As shown in Fig. 3.5, 98% of the light energy entering the splicing prism can be utilized, so it is often used in high-resolution visible spectral cameras with small relative aperture and insufficient light energy. Total reflection and total transmission film forms a light barrier to the transmission area, and the transmission area without reflection film also forms a light barrier to the reflection area. Therefore, the illumination on the focal plane detector does

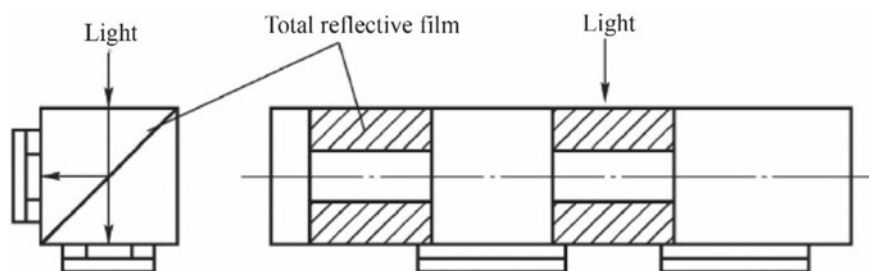


Fig. 3.5 Sketch of total reflection and total transmission optical stitching Reprinted from Ref. [1] copyright 2003, with permission from China Aerospace Publishing House

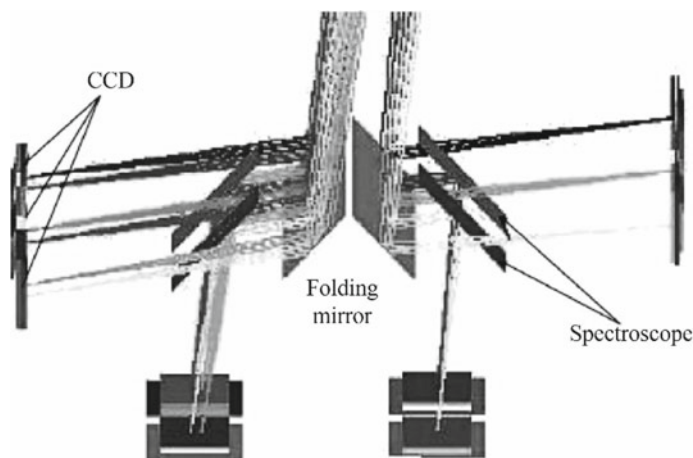


Fig. 3.6 Pleiades double mirror stitching scheme. Reprinted from Ref. [2], copyright 2016, with permission from Spacecraft Engineering

not change from full illumination to full shielding abruptly, but in gradual process, resulting in the “vignetting” phenomenon. In order to get the information in the light-shielding area as completely as possible, it is also necessary for adjacent detectors to have overlapping pixels, so that the energy of the pixels in the light-shielding area can be added together in the process of ground image processing to compensate the signal. This optical stitching scheme has been adopted by ZY-3, GF-2, and other satellites in China.

(d) Mirror Stitching

Mirror stitching divides the image plane of the camera through two rows of reflecting mirrors with staggered arrangement and projects to two small image planes perpendicular to the original image plane. On the one hand, compared with the common field of view stitching, it is no longer subject to the detector size, which can reduce the gap between the two rows of detectors, thus reducing the influence of the number of overlapping pixels; on the other hand, it also avoids the problem of vignetting in the stitching area of two adjacent detectors in optical stitching. The French Pleiades satellite uses exactly this stitching method, as shown in Fig. 3.6.

3.4.12.2 Analysis of Stitching Accuracy

The image quality can be ensured by the required stitching accuracy of multiple detectors, such as the lap joint precision between the two detectors and the straightness and parallelism of the two rows of detectors after stitching. Generally, the registration requirements for different spectral bands in multispectral camera accuracy are better than 0.1–0.2 pixels. For single-spectral cameras, this requirement can be

appropriately reduced. The confocality of each detector component is required to be $1/n$ ($10 > n \geq 2$) of a $1/2$ focal depth of the lens.

For high-resolution visible spectral cameras, the lapping accuracy deviation between two CCDs is generally required to be less than $3\text{ }\mu\text{m}$ if the pixel size of panchromatic detector is $8\text{--}10\text{ }\mu\text{m}$; the collinearity deviation after stitching of each row of CCDs is less than $4\text{ }\mu\text{m}$; the parallelism deviation of two rows of CCDs is less than $5\text{ }\mu\text{m}$; and the coplanarity deviation of each TDCI CD pixel is less than $10\text{ }\mu\text{m}$.

3.4.13 Analysis and Design of Focal Plane and Imaging Circuit of Camera

3.4.13.1 A/D Quantization Bit Determination

Analog-to-Digital (A/D) quantization is to convert video signals into digital signals for easy transmission. The selection of quantization bits affects the imaging quality to a certain extent. Quantization noise can be reduced by using high quantization bit. In addition, the number of quantization bit is proportional to the dynamic range of the image, which can improve the image quality to some extent. Under the premise of satisfying the high SNR of video signal, more scene information is reflected by high quantization bit.

For typical high-resolution visible spectral remote sensing satellites, such as IKONOS-2, WorldView series, and GeoEye series, the image quantization bit is mostly 11-bit. Some satellites use 12-bit quantization, such as Pleiades. The selection of quantization bit is mainly determined by the design factors such as camera noise level, dynamic range, and data volume. Therefore, it is not advisable to blindly pursue higher quantization digits. The corresponding examples are analyzed as follows:

- (a) If the dark background noise (under conditions of photon-free shot noise) of the camera circuit is 2.5 mV and the saturation voltage is 2 V , the quantization corresponding to 12-bit accounts for 5 DN values, that is, the low 2-bit signal of 12-bit has been submerged by noise as invalid data, and the circuit noise will still increase with the increase of illumination intensity, mainly due to the increase of photon shot noise. Therefore, the output quantization bit of the camera is allowed to be less than 10-bit.
- (b) Under the condition of minimum radiance input, i.e., the solar elevation angle is 20° and the ground reflectance is 0.05, if the camera adopts default integral grade and gain settings, and the noise of the camera circuit is 2.75 mV , the corresponding quantization of 12-bit accounts for 5.5 DN values, less than 8 DN values (corresponding to 3-bit). Therefore, in order to preserve the effective signal of the image, the output quantization bit of the camera should be >9 -bit.

- (c) According to the formula of quantization noise for SNR, $N_{AD} = \frac{x}{\sqrt{12}}$, where x is a voltage value represented by a bit, with $x = \frac{2V}{2^{10}}$, the 10-bit quantization noise is obtained as 0.56 mV, which contributes less to noise.

In summary, it is reasonable to use 10-bit as the quantized bit in the camera system, by which the interface matching design between camera subsystem and data transmission subsystem should be carried out accordingly.

In short, a high quantization bit can reduce quantization noise, but only if the video output noise of the camera is reduced. The matching of the two is reasonable.

3.4.13.2 Noise Analysis and Suppression Technology

The noise model of high-resolution visible spectral camera is shown in Fig. 3.7. From the input of incident light to the output of digital video signal, the noise generated by almost every process is superimposed on the signal. Therefore, the digital quantity of each pixel includes both signal component and noise component. Main noise sources are: photon shot noise N_{SN} , detector dark current noise N_D , CCD readout noise N_{READ} , pre-discharge circuit noise N_{PA} , signal processor noise N_{PR} , quantization noise N_{AD} , and driving and power supply interference noise N_{EMC} .

- (1) **Photon shot noise** is caused by the random fluctuation of the photons arriving at the sensor, and its value is proportional to the square root of the accumulated charge on the detector. It is the inherent noise of TDI CCD devices, which cannot be suppressed by the off-chip processing circuit.
- (2) **Detector dark current noise** is greatly affected by the temperature of CCD. The dark current noise increases about 1/2 times when the temperature rises by 7 °C. Taking Corona device as an example, the corresponding relationship is shown in Table 3.5.

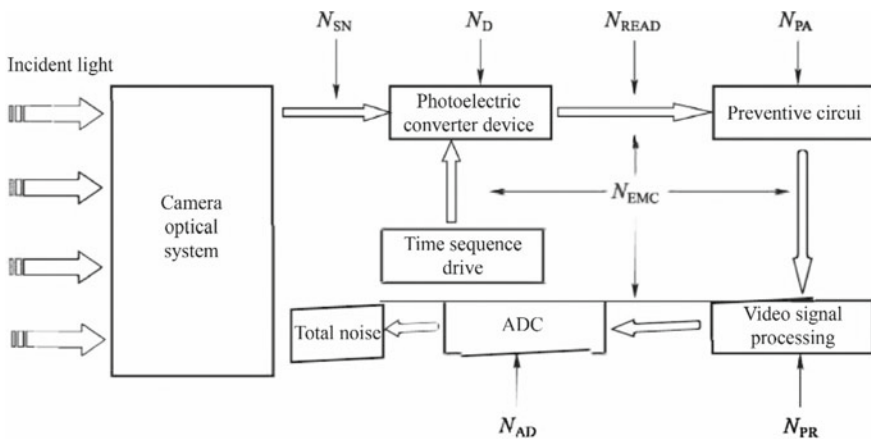


Fig. 3.7 Noise model

Table 3.5 Dark current noise output corresponding to detector operating temperature

Detector operating temperature/°C	18	25	32	39
Dark current noise output/mV	0.08	0.12	0.17	0.25

Dark current noise is caused by the random fluctuation of the number of photons arriving at the sensor. Its value is proportional to the square root of the accumulated charge on the detector. It is the inherent noise of TDI CCD devices. The off-chip processing circuit cannot suppress this noise.

- (3) **CCD readout noise** reflects its own noise level, which cannot be suppressed by the off-chip processing circuit. By adopting low-noise TDI CCD, the readout noise can be effectively reduced to about 0.53 mV.
- (4) **Pre-discharge circuit noise** is mainly from operational amplifier noise. The main measure to reduce the noise of pre-discharge circuit is to use low-noise operational amplifier, such as LMH6715 operational amplifier with a noise value of about 0.1 mV.
- (5) **Quantization noise** is directly related to quantization bit. For a 10-bit quantized camera, the quantization noise value is 0.56 mV.
- (6) **Signal Processor Noise:** The integrated signal processing chip can realize camera-related double sampling, amplification, and quantization functions within the chip, thus reducing the external interface and signal transmission processes, and avoiding unwanted noise. For example, OM7560 is an integrated signal processing chip that meets the high-quality requirements of aerospace and has good noise performance. The noise of the signal processor is 0.5 mV under a bandwidth of 175 MHz.
- (7) **Driving and power supply interference noise**, which is from power supply, driving time synchronization, and other high-frequency signals, can interfere image signal during generation and transmission. Therefore, a series of effective measures to suppress interference noise are provided in circuit design. The interference noise can be reduced to 2.5 mV by taking measures, which mainly includes adopting the design idea of driving circuit and signal processing circuit in the preposition to reduce the interference of the strong driving signal to the weak image analog signal; using the grounding wire with shielding performance to isolate each detector to form an independent electrical environment space; and adopting distributed independent detector power supply system to prevent crosstalk during signal transmission. In addition, independent power supplies and decoupling circuits are also used for circuits, drives, analog circuits, and digital circuits of different taps within the same detector.

3.4.13.3 Clamp Correction Technique

Camera on-orbit imaging is affected by the pedestal voltage of camera circuit, atmospheric scattering, and stray light, which enhance the background of the image and make a foggy appearance appear in the image, thus affecting the gradation and

quality of the image. Therefore, the background of this image should be deducted. The clamp processing function of the camera can remove the background of the image by adjusting the signal bias on the one hand, and improve the contrast of the image and the clarity of the dark target effectively by stretching the image on the other hand. The specific way is to process the digital image signal. Clamping correction can be used as an optional function option of the camera, setting a function switch, so that users can choose to download the original image or choose to download the image after clamping correction according to different needs of use.

For digital circuit, dark background negative clamping processing method is a method, in which signals are quantized through the camera A/D quantization chip in high quantization bit (e.g., 12 bits), then are input into the signal processing circuit, in which the digital image is adjusted by overall downwards offset (i.e., image background clamping) and gray stretching, and then part of the quantized high bit is output (e.g., higher 10 bit in 12-bit output) to data transmission system. The processing parameters such as clamping and stretching of digital image, are recorded in the image auxiliary data, and correspond strictly with each row of image data in the figure, which is convenient for further radiation correction on the ground. Before the task is formulated, the appropriate clamping parameters can be selected according to different atmospheric and imaging conditions, so as to improve the imaging quality.

Figure 3.8 shows the image of Beijing airport before gray clamping and stretching of SPOT-5 (8-bit quantization), and Fig. 3.9 is the same image after gray clamping and stretching. It can be seen that the image before processing has a background gray level with a narrower histogram and blurred target; the background gray level of the image after processing is deducted, the histogram distribution is balanced, and the target contrast is higher.

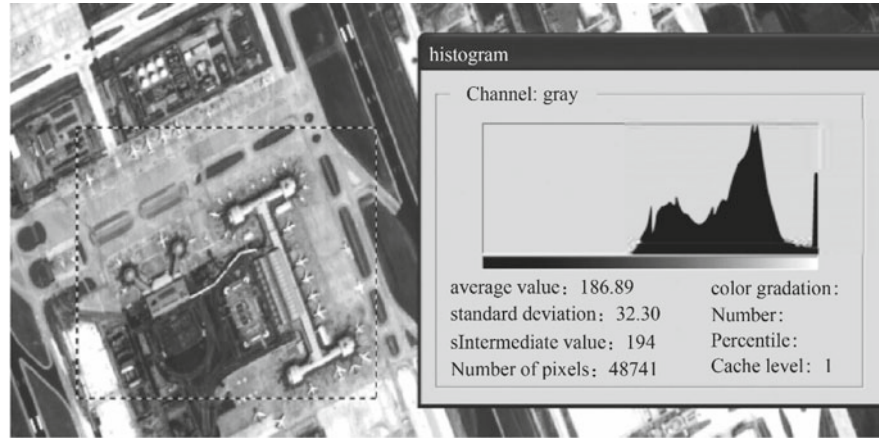


Fig. 3.8 Zero-level image of SPOT-5

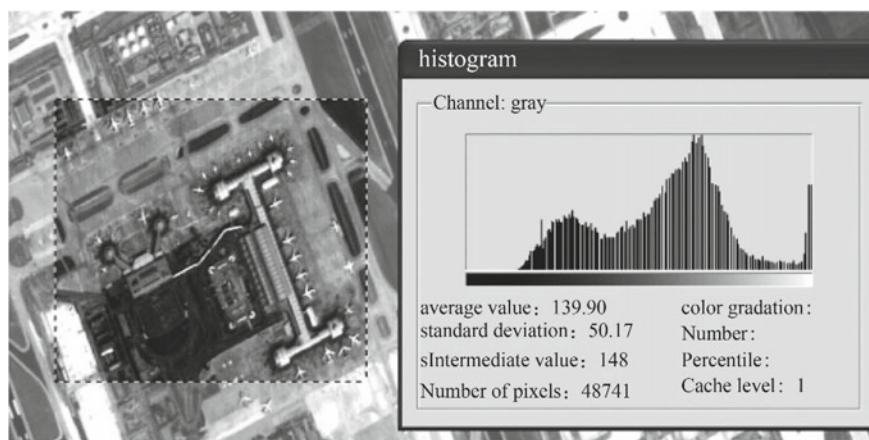


Fig. 3.9 Partially processed image of SPOT-5

At present, the satellite design is usually based on the on-board 12-bit quantization and output 10-bit clamp correction technology. The main advantages are as follows:

- (1) After subtraction and grayscale stretching processing of the digital image background, the gradation can be filled as much as possible to the camera's entire quantization range of 1024 DN, which enhances the image contrast;
- (2) When imaging dark target, the 12-bit digital image is subjected to histogram stretching processing and then a part of upper 10-bit is output, and the effective signal in the lower 2 bit can be stretched to output in the upper 10-bit image, thus retaining the information of the partial dark target and enhancing recognition ability;
- (3) Compared with the ground stretching process, high-frequency information of the image can be more easily retained by histogram stretching processing of the original data before image compression on-board.

3.4.14 Design of Focusing System

When a high-resolution visible camera is on orbit, the focal plane position of the camera will be changed by mutative ambient temperature or mechanical conditions, which will result in the decrease of the modulation transfer function of the system. Generally, the image quality of the camera will degrade obviously if the defocus of the camera exceeds $1/2$ focal depth. Therefore, a focusing mechanism should be provided for the high-resolution visible spectral camera, and its focusing control accuracy is generally better than $1/20$ focal depth to minimize the influence of defocusing on the modulation transfer function of the system.

The image plane adjustment methods commonly used in total reflection optical imaging system include lens group focusing, focal plane focusing, and plane mirror

focusing. The lens group focusing is realized by adjusting the position of the mirror. For a camera with multiple off-axis aspheric mirrors, the optical interval of aspheric mirrors has strict control requirements, so it is not suitable for a focus optical element. Focal plane focusing can adjust the position of focal plane by moving the focal plane forward or backward, but it is necessary to solve the problem that the focal plane electronics wiring harness and the focal plane heat dissipater moving together with the focal plane by forward or backward focusing. Plane mirror focusing is to add a planar mirror in the optical path. The planar mirror moves forward and backward to adjust the imaging position of the image plane in the focal plane. Plane mirror focusing is widely used in the design of high-resolution visible satellite.

3.4.15 Thermal Optical Stability Design

After satellite injection, the focal plane position, optical axis direction, focal length and image distortion of the camera will vary with ambient temperature conditions, so as to decrease dynamic modulation transfer function and geometric positioning accuracy on orbit. Therefore, in the design of the camera, the high-precision thermal control design should be carried out under consideration with the reasonable layout of the optical system and the compatibility and matching of optical materials with the optomechanical structure of the camera to ensure the thermal stability of the camera on orbit. Based on thermo-optical design analysis, thermo-optical stability design of camera mainly includes the following:

- (a) evaluation of material matching, mechanical stability, and thermal stability of optomechanical system;
- (b) determination of on-orbit temperature adaptability of camera system;
- (c) specifying temperature stability and temperature gradient requirements for key components of optical system;
- (d) proposing high-precision and high-stability thermal control scheme;
- (e) putting forward the active compensation or correction scheme for the surface and image quality degradation caused by environmental temperature changes.

3.4.16 Mechanical Stability Design

The camera's focal plane position, optical axis orientation, focal length, and image distortion will be changed under the influence of the factors such as the mechanical vibration in the satellite launching phase, and the weightlessness and stress release in the initial injection, thus affecting the image quality and positioning accuracy on orbit. Therefore, the mechanical stability of the camera optomechanical system should be considered in the design of the camera to ensure the stability of the camera on orbit.

In terms of structural stability control of mirror assembly, the influence of gravity on the mirror surface is reduced by the lightweight design of the large-scale mirror and increasing the specific stiffness of optical elements; the mechanical/thermal matching of optomechanical structure is realized by the flexible design of support structure, which can not only solve the problems of the assembly stress of mirror and thermal stress release on orbit, but also provide a vibration isolation and vibration reduction influence to a certain extent. In the processing, assembling, and adjusting process, it is necessary to ensure that the large mirror assembly has enough resistance to stress and deformation. In the optical processing, modification, assembling, and coating process, the process, in which the stress is introduced, should be strictly controlled, and the stress relief measures, such as vibration test and thermal vacuum test, should be taken.

In terms of structural stability of the frame assembly, materials with a small linear expansion coefficient are used as much as possible, the frame components are assembled unstressed, ensuring the system's operating environment temperature and reducing the sensitivity of the lens with the change of ambient temperature. The thermal compensation design of the optomechanical structure is implemented by the mutual compensation between the thermal expansion coefficients of the optical component and the structural member, thereby further improving the environmental adaptability of the camera structure, and eliminating the assembly stress by the mechanical vibration test and the thermal vacuum test.

3.5 High-Resolution Visible Spectral Camera Solution Description

The design of a high-resolution visible spectral camera is generally described by focal length, field of view, optical system type, number of detectors, and pixel size. For example, a high-resolution visible spectral camera uses an off-axis three-mirror optical system with a focal length of 10 m and a FOV of 3.5° , and 10 pieces of panchromatic TDI CCD at $10\text{ }\mu\text{m}$ or multispectral TDI CCD with a five-spectrum combination at $40\text{ }\mu\text{m}$. With the push-broom imaging method, the camera images the ground scene on focal plane TDI CCD by off-axis TMA optical system. The optical signal is converted into electrical signal output. The electrical signal is processed by the signal processing circuit and then transmitted to the ground station through the data transmission subsystem.

3.5.1 Definition of the Main Functions of the Camera

The main functions of the camera include the following:

- (a) **Dynamic adjustment function of on-orbit integration time:** The image shift velocity of the ground object on the focal plane of the camera changes dynamically on orbit, so the integration time of camera should be dynamically adjusted to match image shift, and the integration time range should meet the imaging requirements of satellite's on-orbit attitude maneuver range.
- (b) **On-orbit integral grade and gain adjustment function:** During the satellite on-orbit mission, because of the large radiation brightness difference of the input ground objects, the TDI integral grade and gain of the camera should be adjusted on-orbit according to different imaging conditions to obtain better image dynamic range.
- (c) **On-orbit focusing functions:** There is a strict matching relationship between imaging object distance and image distance of optical system. With focusing function, the camera could adapt to the micro-change of optical system caused by the space environment after injection and the change of object distance brought by different attitude imaging.
- (d) **Thermal control function:** Due to the strong influences of the changed space heat flux on orbit, a high-precision thermal control system is provided to ensure that the optical system works in a stable temperature environment, thus ensuring the on-orbit dynamic imaging quality.
- (e) **High-precision time synchronization and punctuality function** can ensure the consistency of time data benchmarks and time accuracy at every stage, such as injection, attitude adjustment, and imaging, and improve the geometric positioning accuracy of images.

3.5.2 Design Constraints

3.5.2.1 Mission-Level Design Constraints

The mission-level design constraints of the visible spectral remote sensing satellite system are mainly from the application requirements, including the application indicators, such as the orbit of satellite, imaging spectrum, resolution of ground pixels and swath, and other key imaging quality indicators, such as on-orbit dynamic modulation transfer function and SNR.

For visible spectral remote sensing satellites, the design constraints of illumination conditions and solar altitude angle should be considered, and the solar synchronous orbit is usually selected. Considering the application requirements of solar irradiation conditions for spring, summer, autumn, and winter, the orbit is usually chosen with the local time of descending node at 10:30 a.m. or 1:30 p.m., and the orbital altitude is generally in the range of 450–800 km.

3.5.2.2 Design Constraints for Large Engineering Systems

Visible spectral cameras should receive auxiliary data from on-board bus broadcasting, arrange the data together with the auxiliary data and images of visible spectral cameras, and send them to the ground application system. The camera with the total field of view distortion of better than 1.5%, the distortion measurement accuracy of better than 5 pixels, the absolute calibration accuracy of above 7%, and the relative calibration accuracy of better than 3% is used for ensuring the quality of geometric imaging.

3.5.2.3 Satellite Overall Design Constraints

In order to ensure the interface matching of the whole satellite, the following design constraints of the camera system can be derived from satellite system:

- (a) the static MTF of the full chromatographic segment of the camera: better than 0.2;
- (b) the static MTF of the multispectral section: better than 0.3;
- (c) the low-end SNR: better than 20 dB (solar altitude angle of 20°, ground object reflectance of 0.05);
- (d) the high-end SNR: better than 48 dB (solar altitude angle of 70°, ground object reflectance of 0.05);
- (e) the response inconsistency between TDI CCD channels: $\leq 5\%$.

In order to ensure the interface matching between the visible spectral camera and other subsystems on the satellite, the weight, long-term and short-term power consumption, and quantization bit of the visible spectral camera should be specified. Satellite's on-orbit assessment life is 5–8 years, and camera design life should meet the requirements of “1.5 years for satellite assembly, 1-year for storage and 5–8 years for on-orbit operation”.

3.5.3 System Configuration and Topology

The camera subsystem is generally composed of a camera body and an electronic computer (Fig. 3.10). The camera body mainly includes an optical system, a focusing component, a focal plane component, a lens hood component, etc., which is responsible for the conversion of the ground scene to the electronic image. The electronic computer is mainly composed of a management control module, a bus communication module, a power supply and distribution module, a signal processing module etc. Its main function is to receive the whole satellite primary bus power supply, supply power for the camera electronic system, receive commands and related parameter information through the bus, control the camera, and feedback engineering parameters to the satellite.

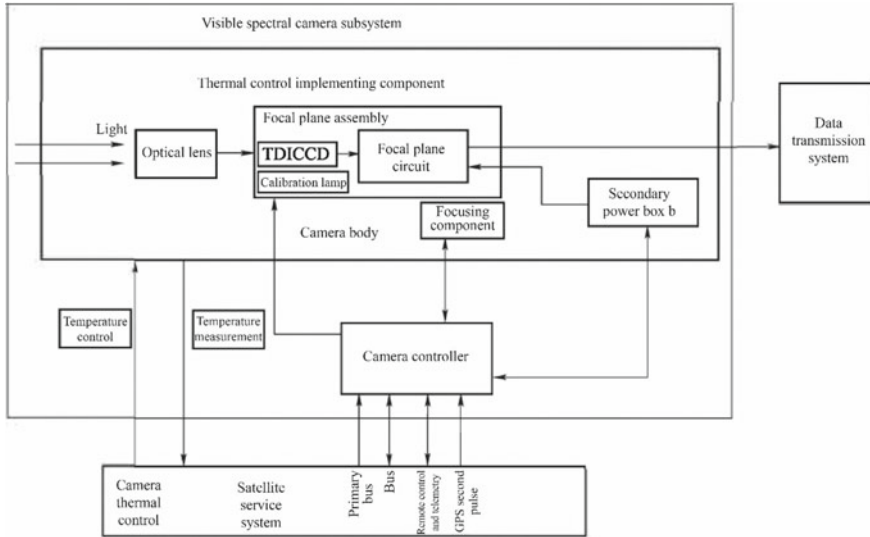


Fig. 3.10 Principle diagram of camera subsystem composition

3.5.4 Operating Mode Design

Waiting mode: In the waiting mode, only the remote sensing circuit and thermal control of the camera are in a long-term operating state, while other devices are in shutdown state.

Imaging mode: Imaging mode is divided into the same-integral time imaging mode and the different integral time imaging mode. In the same-integral time imaging mode, each CCD operates with the same integration time and outputs the captured image data of the ground scene. In the different integral time imaging mode, each CCD operates with different integration time and outputs the captured ground scene image data.

Focusing mode: In the focusing mode, the focal plane position of the camera is adjusted through the focusing mechanism, and the direction and number of steps to be adjusted for the focal plane are determined based on the imaging quality before and after focusing. Focusing can be done separately or during the imaging process. The imaging mode and the focusing mode can be shared.

Self-check mode: Includes both calibration mode and self-calibration graphics mode. The calibration mode is carried out at night when the satellite is in the shadow of the Earth. The camera images the on-board calibration lamp to obtain relative calibration image data. In the self-calibrating graphics mode, the focal plane CCD is not powered, and the pre-stored self-calibrating graphics data is output to the data transmission subsystem.

3.5.5 Camera Optical System Design

A high-resolution resource camera adopts an off-axis three-mirror, noncentral obstruction, and non-intermediate image optical system. The optical system consists of three aspheric mirrors (a primary mirror, a secondary mirror, and a tertiary mirror) and a plane mirror (located between the image plane and the tertiary mirror). The full field average designed MTF is better than 0.45. The structure of the optical system is shown in Fig. 3.11, and its optical design scheme is shown in Table 3.6.

The camera adopts an off-axis optical system. The optomechanical structure mainly consists of space truss structure component, primary mirror component, secondary mirror component, tertiary mirror component, focusing component, CCD focal plane component, and hood component.

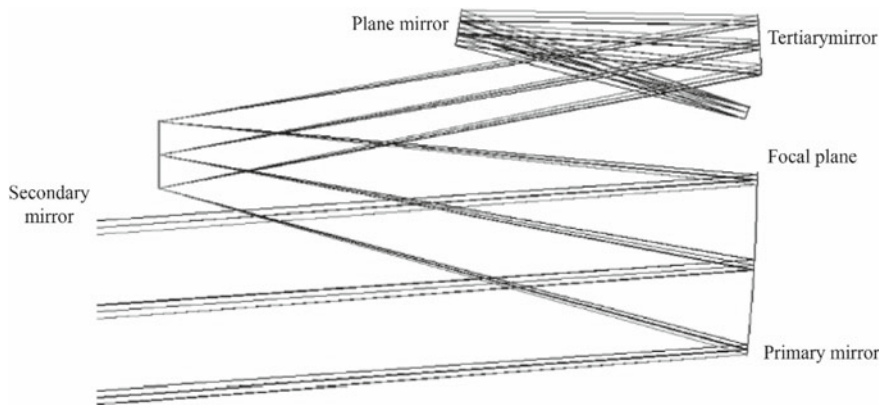


Fig. 3.11 Diagram of optical system structure

Table 3.6 Camera optical design scheme

Parameter	Design results
Spectral segment/ μm	PAN: 0.45 ~ 0.90 B1: 0.45 ~ 0.52; B2: 0.52 ~ 0.60; B3: 0.63 ~ 0.69; B4: 0.76 ~ 0.90
Focal length/m	10
Relative aperture	1/12
FOV/($^{\circ}$)	3.5
Designed MTF	Nyquist frequency 0.45 (average FOV); 1/4 Nyquist frequency 0.65 (average FOV)

3.5.6 Design of Camera Electronic System

Camera electronic system is mainly composed of imaging circuit, camera controller, and camera distribution unit. The task of the imaging circuit is to realize functions such as photoelectric conversion and image data output, which generally include many circuits such as a TDI CCD circuit, a time synchronization control circuit, a driving circuit, an analog preamplifier circuit, a video processing circuit, a data synthesis circuit, and an integration time control circuit. The camera controller is mainly responsible for camera task management, remote command management, high-precision image shift calculation and control, second pulse synchronization signal, telemetry parameter management, focusing control, and other functions. Camera distribution unit is mainly in charge of transforming primary bus power for secondary power supply and tertiary power supply; controlling the sequence of power on/off of CCD, power telemetry acquisition, etc.

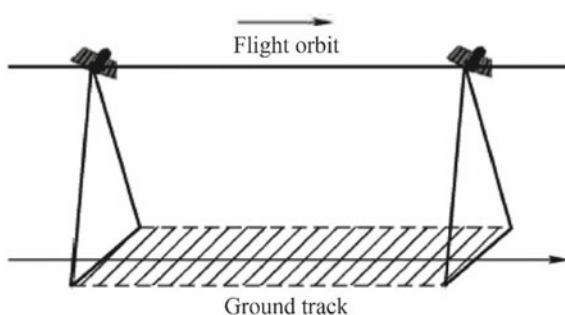
3.5.7 Description of Camera High-Precision Thermal Control Design

Large-aperture and long focus optical systems are very sensitive to temperature level, temperature changes, and temperature gradients, so the requirement of temperature control is very high. However, large-scale cameras are often installed outside the satellite, and the space heat environment is very unsatisfactory. Therefore, the thermal optical design analysis and verification of simulated imaging test in a thermal vacuum environment is very crucial.

For large-scale camera optomechanical system, based on the adequate isothermal design and thermal insulation design, a high-precision distributed active thermal control scheme is adopted according to the on-orbit flight thermal characteristics of the camera. Distributed common-precision temperature control operation is performed on the decentralized optomechanical structure system such as mirror assembly, mirror frame assembly, and camera skin in the camera body to realize integrated and cooperative control of the temperature measurement, heating, and temperature control loops, thus ensuring that the camera optical system operates in a state of high accuracy, stability, and temperature uniformity.

For the camera focal plane module, the thermal power consumption of high-resolution camera TDI CCD and its imaging circuit is extremely large. The power can reach several hundred watts or even kilowatts when operating, however, it is zero when not operating. The thermal power consumption fluctuates greatly. Temperature fluctuations have a great influence on the imaging performance of imaging circuit and optomechanical system. According to the noise control requirements and thermal characteristics of camera detector and imaging circuit, the temperature fluctuation caused by high power consumption fluctuation of focal plane imaging circuit is required to be damped by using the combination of high thermal conductivity heat

Fig. 3.12 Sketch of along-track directional push-broom imaging mode



transfer element and high phase change energy storage element and adopting the active constant temperature thermal control scheme “heat storage → heat dissipation → heat release → heat storage...” to ensure high-precision temperature control of TDI CCD and optomechanical system.

3.6 Design of Satellite On-Orbit Imaging Mode

With the improvement of attitude maneuverability of high-resolution remote sensing satellites, more and more imaging modes can be used on-orbit, such as conventional strip push-broom imaging, one-orbit multipoint target imaging, one-orbit stitched imaging, one-orbit single target multi-angle imaging, and even dynamic imaging and non-along-track direction active push-broom imaging. The imaging capability and observation range of the satellite have been significantly improved.

3.6.1 Along-Track Directional Push-Broom Imaging Mode

Along-track directional push-broom imaging mode is a push-broom imaging method, by which the sub-satellite targets along the orbit are push-broom imaged by satellite in attitude control mode with high precision and high stability. During the imaging period, the yaw angle of the satellite is corrected, but the rolling and pitching angles are unchanged. The sketch of the imaging mode is shown in Fig. 3.12.

3.6.2 One-Orbit Multitarget Imaging Mode

In one-orbit multitarget imaging mode, the satellite images scattered targets through its fast swinging with the fast maneuverability of the satellite, as shown in Fig. 3.13. This imaging mode is mainly for imaging multiple targets in one orbit that are close

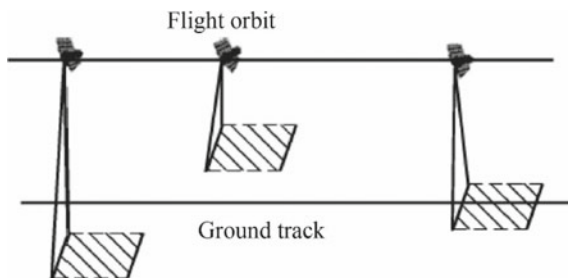


Fig. 3.13 Sketch of one-orbit multitarget imaging mode

to the along-track direction and in different pointing positions by the satellite with a fast attitude maneuverability in rolling and pitching directions.

3.6.3 One-Orbit Stitched Imaging Mode

One-orbit stitched imaging mode is an imaging method, by which the satellite images in the along-track direction multiple times with the fast maneuverability of satellite, and the several obtained images are stitched together to increase the imaging swath. This mode can effectively enhance the imaging coverage range of satellite in the cross-track direction when the observation targets are concentrated and widely distributed in some specific areas and the satellite cannot be completely covered by a single push-broom on one-orbit. The flight mode of the satellite by stitched imaging is shown in Fig. 3.14.

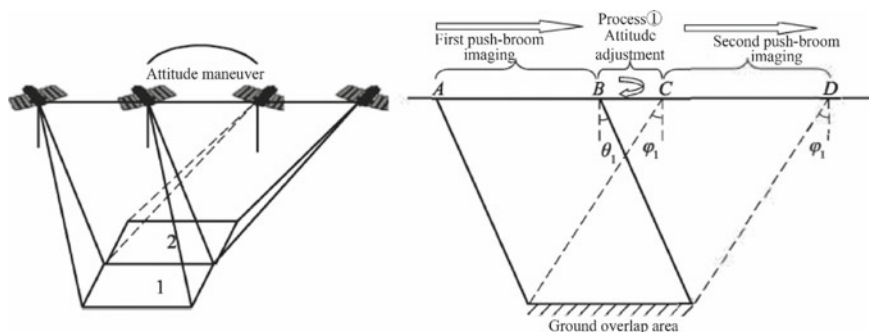


Fig. 3.14 Sketch of one-orbit stitched imaging mode

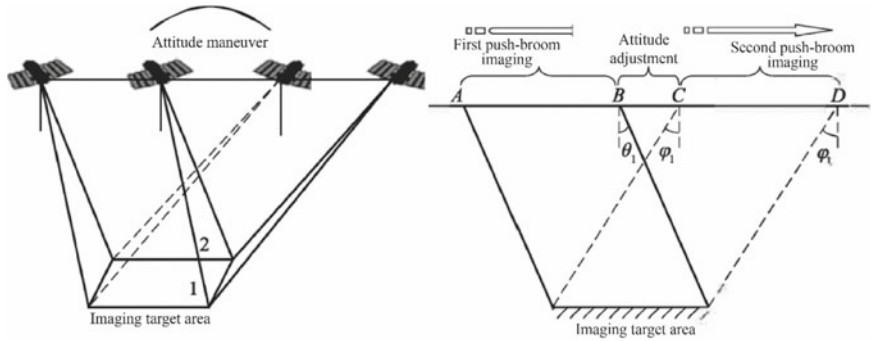


Fig. 3.15 Sketch of one-orbit multi-angle imaging mode

3.6.4 One-Orbit Multi-Angle Imaging Mode

One-orbit multi-angle imaging mode is a continuous tracking and push-broom imaging method for imaging the same ground target with different elevation angles during satellite flight. With several times of push-broom, the image information of the same ground target in multiple different stereo-planes can be obtained, and the omnidirectional stereo image information of this object can be obtained by ground processing. Figure 3.15 shows the flight mode of the satellite when it performs two multi-angle imaging on a single target in one-orbit.

3.6.5 Non-Along-Track Active Push-Broom Imaging Mode

When the observed target is not in the along-track direction, but distributes in an angle to the sub-satellite point trajectory, and the distribution width is within the coverage of a single satellite strip, the satellite has to rotate a certain angle around the Z-axis first, and then images in pitch and rolling two-way active push-broom mode, thus obtaining the satellite images in non-along-track direction. Active push-broom imaging mode in the non-along-track direction is shown in Fig. 3.16. In this mode, the good timeliness for long and narrow objects in non-track direction, such as boundary, river, and coastline can be obtained.

3.7 Analysis and Design of Satellite's On-Orbit Dynamic Imaging Quality

After the visible camera is loaded onto the satellite platform and launched into the space environment, its dynamic imaging quality is affected not only by the camera

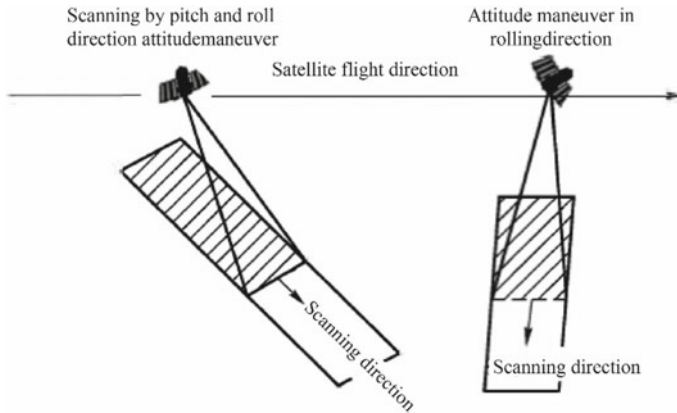


Fig. 3.16 Sketch of non-along-track direction active push-broom imaging mode

itself, but also by the platform, space environment, and on-orbit dynamic flight. Therefore, it is necessary to analyze and control the full-link and full-element imaging quality, which is also the most critical task in the overall design of high-resolution optical remote sensing satellites.

3.7.1 Design Measures for Quality Assurance of Satellite On-Orbit Dynamic Imaging

With the continuous improvement of resolution, it is increasingly difficult to guarantee the full-link and full-element image quality. On-orbit imaging quality design assurance is an important part of the overall design and engineering development of remote sensing satellites. The main assurance factors and control measures are listed in Table 3.7.

3.7.2 High-Precision Image Shift Matching Design

For the TDI CCD imaging system, the prerequisite for clear imaging is that the transfer rate of photo-generated charge packets should be consistent with the motion rate of the image on the focal plane. Any mismatch or mismatch of the rate will result in image blurring, grayscale distortion, and contrast and resolution degradation. To this end, the satellite shall calculate the camera integration time in real time according to the actual orbital and velocity changes on orbit, so as to reduce the imaging quality degradation caused by the scene mismatch of the CCD image.

Table 3.7 Essential factors and control measures of satellite dynamic imaging quality assurance

Serial number	Measures	Program description	Remarks
1	High-precision time synchronization design	Using the high-precision second pulse time synchronization scheme of navigation satellite, a high-precision time-series relationship is established for control, TT&C, and camera subsystem data	Improving radiation quality
2	Integration time setting	Accuracy of integration time calculation is improved by using high-precision navigation receiving equipment, and integration time are set for camera subfield	
3	Flutter suppression	The high stiffness structure design of the camera and the vibration isolation design of the mechanical interface between the satellite platform and the camera are adopted to ensure that the camera adapts to the on-orbit thermodynamic changes. Adequate vibration isolation design is adopted for the main disturbance sources (such as CMG) on the satellite to reduce the impact of high-frequency flutter on the image	Improving radiation quality
4	Multi-sensor attitude determination	Reasonable layout of attitude measurement equipment such as star tracker, using multi-sensor attitude determination to achieve high attitude measurement accuracy	Improving geometric quality
5	Improving orbit determination accuracy	Improving orbit determination accuracy by using high-precision navigation receiving equipment	

(continued)

Table 3.7 (continued)

Serial number	Measures	Program description	Remarks
6	Stability of angle between camera and star tracker optical axis	The integration and isothermal design of camera and star tracker are adopted to ensure the stability of the angle between camera and star tracker during orbital operation	
7	Reasonable arrangement of auxiliary data	Downlink star tracker and gyroscopic data and high-precision time synchronization information; increase downlink frequency of attitude and orbit data, etc.	
8	Angular displacement measurement	The flutter data of satellite are measured by a high-precision angular displacement measuring device, and the ground data can be downlinked as reference data for ground image correction	

3.7.2.1 Integration Time Design

Based on satellite orbital parameters and camera design parameters, the integration time range of camera imaging can be calculated. The minimum integration time can be calculated with the orbital parameters of the sub-satellite point at the minimum altitude and the maximum elevation of 8.848 km. The maximum integration time can be calculated with the orbital parameter of the maximum attitude maneuver angle at the maximum orbital height and the elevation value of 0 km. For example, assumed that the altitude of normal orbit of source remote sensing satellites is 460–500 km, the maximum eccentricity is 0.0025, and the maximum offset of semimajor axis is ± 2102.75 m, the integration time range of the camera can be calculated to be 64–130 μ s according to the design parameters such as camera focal length and pixel size. The camera imaging circuit design must consider the integration time range under extreme conditions such as orbit and attitude maneuvering, and leave a margin.

3.7.2.2 Integration Time Subfield Setting Method

For visible spectral remote sensing satellites with a GSD of better than 1 m and as watch of tens of kilometers, the effective field of view of the satellite shall be

Table 3.8 MTF Degradation at the center and the edge of field of view when the integration time is set all based on the center point

Pitch (°)	Roll (°)				
	0	10	20	30	45
45	0.899	0.907	0.601	0.170	0.081
30	0.978	0.954	0.812	0.545	0.096
20	0.991	0.965	0.847	0.625	0.037
10	0.997	0.964	0.858	0.662	0.127
0	0.999	0.962	0.854	0.665	0.142

Note The highlighted data is values by MTF > 0.95

designed as multi-TDI CCD stitching form. The projection size of each TDI CCD pixel on the ground varies with the imaging field of view of each TDI CCD, which leads to differences in image shift velocity. If each TDI CCD is still set uniformly according to the integration time of the center point, the MTF of the edge field image is degraded by the mismatch of image velocity, especially after the large-angle rolling attitude maneuver. Table 3.8 shows the MTF degradation at the center and the edge of field of view when the integration time is set all based on the center point (with 500 km orbital height, focal length 10 m, and field of view angle 3.4°).

In order to ensure the modulation transfer function of full field of view imaging, the high-precision integration time shall be calculated in real time for detectors with different fields of view, and set for different fields of view. Table 3.9 shows the improvement of MTF at the center and edge of field of view when the integration time of the subfield is set. It can be seen that the MTF at the edge of field of view can be significantly improved by setting subfield integration time.

Table 3.9 MTF improvement of the center and the edge field of view when the integration time of the subfield is set

Pitch (°)	Roll (°)				
	0	10	20	30	45
45	0.990	0.980	0.966	0.952	0.861
30	0.999	0.995	0.989	0.983	0.956
20	0.998	0.999	0.993	0.988	0.966
10	0.998	0.997	0.994	0.990	0.976
0	0.991	0.983	0.966	0.952	0.861

Note The highlighted data is the values by MTF > 0.95

3.7.2.3 High-Precision Image Shift Matching Control

For high-resolution visible spectral cameras, the processes, such as velocity–height ratio calculation, focal length measurement, integration time setting delays, will cause integration time setting errors. For the TDI CCD camera, the accuracy of integration time setting will affect the imaging quality. The MTF degradation caused by the integration time setting error is calculated using the following equation:

$$\Delta d = m \cdot c \cdot \Delta t_i,$$
 (3.12)

$$MTF(N) = \sin c(\pi v_n \Delta d),$$
 (3.13)

where m is the integral grade, Δt_i is the integration time setting error, v_n is the sampling frequency $1/(2c)$ (c is the pixel size), and Δd is the image shift caused by the integration time setting error. Table 3.10 shows the influence of the integration time setting error on the MTF.

The calculation results show that under the 48th integral grade, when the integration time setting accuracy is less than 0.5%, the MTF degrades by 2.3%, which has little influence on the imaging quality. However, when the integration time setting accuracy reaches 0.5%, the integral grade is increased to 96, and the MTF will be degraded by 9.21%, which will seriously affect the imaging quality.

The integration time setting accuracy depends on various parameters, such as the test accuracy of detector pixel size, camera focal length test accuracy, calculation accuracy of satellite’s velocity–height ratio, integration time setting delay error, and integration time quantization error, each of which will be assigned an index as follows to meet the error requirement of integration time setting accuracy of less than 0.5%:

- (a) the accuracy of focal length measurement of less than 0.1% is ensured by high-precision autocollimation and precise optical ranging;
- (b) TDI CCD size measurement error is given by detector manufacturers, which can be generally ignored;
- (c) the computation accuracy of the velocity–height ratio mainly depends on satellite’s velocity measurement error, digital elevation instrument error used on satellite, satellite’s positioning error, and attitude measurement error. Assuming that the satellite orbital height H_e is 500 km, the errors are analyzed as follows:

Table 3.10 The relationship between MTF and different grades and errors of setting accuracy

MTF		Integral grade				
		16	32	48	64	96
Error of out-of-sync time	0.3%	0.9995	0.9952	0.9915	0.9809	0.9662
	0.5%	0.9985	0.9867	0.9765	0.9476	0.9079

- i. For the velocity measurement error $\Delta V_G \leq 0.2$ m/s, the error of velocity–height ratio caused by the velocity measurement error is 2.9×10^{-5} .
 - ii. If the elevation error ΔH_1 in the whole range of digital elevation maps does not exceed 500 m, the error of the calculation of velocity–height ratio caused by the elevation error is $\left| \frac{\Delta H_1}{H_e} \right| \leq 1.0 \times 10^{-3}$.
 - iii. If the positioning error component ΔH_2 of the satellite along the orbital altitude does not exceed 10 m, the error of the calculation of velocity–height ratio caused by the positioning error component is $\left| \frac{\Delta H_2}{H_e} \right| < 2.0 \times 10^{-5}$.
 - iv. If the maximum yaw angle of the camera is 45° and the yaw angle error is 0.05° (attitude control pointing error), the introduced photographic distance error ΔH_3 is about 617 m, then the error of the calculation of velocity–height ratio caused by them is $\left| \frac{\Delta H_3}{H_e} \right| < 1.23 \times 10^{-3}$.
- (d) Assuming that the frequency of the quantization clock for converting the data of the velocity–height ratio into the integration time code is 7 MHz, the corresponding quantization error is up to 1.43×10^{-7} s per a bit, when the integration time is 65 μ s, the maximum error is 2.2×10^{-3} .
- (e) The on-board electronic system calculates the integration time based on the attitude data from attitude measurement system and the orbit data from the positioning system. The organization of every equipment data, the inter-equipment transmission of data and the final calculation of integration time all require a certain amount of time. For a certain moment, the integration time cannot be obtained in real time, but has a certain delay. In general, a delay error of the integration time calculation link is less than or equal to 1‰.

3.7.3 Image-Aided Data Design

3.7.3.1 Auxiliary Data Design Related to Geometric Quality

The satellite attitude data, orbit data, and image line exposure time required for ground geometric positioning accuracy processing are resolved all based on the auxiliary data output from each satellite subsystem. Therefore, the satellite auxiliary data content, data format, and data update frequency will directly affect the ground processing positioning accuracy. Auxiliary data related to geometric quality mainly includes:

- (a) **Satellite positioning data:** The position and velocity at imaging time provided by navigation receiver mainly include positioning data time information, orbit position, velocity, positioning tag, integration time, etc. The general update frequency is 1 Hz;
- (b) **Satellite attitude data** provided by the control system mainly include attitude determination mode tag, star tracker data validity tag, satellite attitude data and time, etc. Generally, the general update frequency is ≥ 4 Hz.

- (c) **The imaging time angular velocity provided by gyroscope** mainly include gyroscope and attitude data time information, inertial attitude angular velocity, etc. The general update frequency is ≥ 4 Hz.
- (d) **Integration time and its time information** should be accurate to microsecond level;
- (e) **Exposure imaging line time information** includes the second- and microsecond-level time corresponding to each line of imaging. The error between line time information and whole satellite time reference can be limited to less than 0.1 ms by using high-precision time synchronization design.

In addition, in order to further improve the accuracy of geometric positioning, the auxiliary data can be designed as follows: on the one hand, in order to avoid the on-board computing errors due to incapable complex operations on the satellite by the on-board computer, the original quaternion values from three star trackers are simultaneously output and downloaded together with its high-precision time information to ground station, that provide high-precision on-orbit raw data for high-precision satellite attitude calculation on the ground station, and improve the accuracy of attitude calculation; on the other hand, the original data of the high-precision three-floating gyroscope and fiber optic gyroscope are output into the satellite auxiliary data, and the attitude data of gyroscope and its high-precision time information data in the attitude data of the satellite auxiliary data are downloaded to ground station, by which can effectively guarantee the attitude measurement accuracy when some star trackers are unable to operate.

3.7.3.2 Auxiliary Data Design Related to Radiation Quality

The auxiliary data related to the radiation quality refers to the state parameters related to the imaging of the camera, which are indispensable state parameters for ground image radiation quality processing and characterize the operating state and parameters of the camera imaging. The auxiliary data include various parameters, such as integral grade, gain, offset, as well as the histogram equalization coefficient and the background subtraction coefficient, indicating the parameter values of the camera's original digital image for clamping processing.

3.7.4 High-Precision Time Synchronization Design for Whole Satellite

With the high-precision time synchronization scheme that time reference is uniformly calibrated by the second-pulse-based hardware, the time synchronization errors among the related subsystems on satellite are effectively reduced and the geometric positioning accuracy of the image is improved.

The scheme combines seconds pulse and second-level time bus broadcasting as follows:

- (1) The on-board computer generates hardware second pulse signals at every full second and sends them to the timing subsystem, such as the camera and the control system, with time synchronization accuracy better than $1\ \mu\text{s}$.
- (2) After sending the hardware second pulse time reference, the full second value of the second pulse is sent through the bus. Each timing subsystem counts the time using its own clock, and subdivides the middle time of each full second reference, thus realizing the high-precision time management of less than $0.1\ \text{ms}$ for the whole satellite.
- (3) The subsystems with high-precision time synchronization include cameras, star trackers, and gyroscopes of control subsystems.

The main factors affecting the time synchronization accuracy of the satellite include the following.

The errors caused by the time sending part, which mainly include the errors of hardware second pulse and accurate time accuracy precision (generally not more than $1\ \mu\text{s}$); the time delay in the transmission of hardware second pulse signal to the timing system (usually within tens of μs), that is, the total error of time sending part is not more than $2\ \mu\text{s}$; the second pulse time-correcting error of timing subsystem, which mainly includes the delay of timing subsystem in the period from receiving the second pulse signal to inputting the related data into the auxiliary data, including intra-board line delay, inter-board transmission delay, and device delay, which are generally in the ns magnitude; local timing error of the timing subsystem, which is affected by the accuracy of local clock. For example, if the frequency stability of local clock is $\pm 20\ \text{ppm}$ (ppm is 10^{-6}), then this error is about $20\ \text{ppm} \times 1\ \text{s} = 20\ \mu\text{s}$, and the second pulse time-correcting error of timing subsystem is not more than $20\ \mu\text{s}$.

3.7.5 On-Orbit Dynamic MTF Analysis

During satellite on-orbit dynamic imaging, camera on-orbit imaging has large differences in the along-orbit and the cross-orbit directions because of satellite motion. The main factors affecting the on-orbit dynamic MTF of satellite include atmosphere, camera static MTF, camera push-broom, integration time accuracy, drift correction accuracy, flutter influence, space environmental impact, stray light influence, focusing influence, etc. The whole imaging link system is regarded as a linear system of space frequency, as shown in Fig. 3.17. The integrated modulation response of the whole system is determined by cascade multiplication of the MTFs with these influence factors. The overall response of the system can be expressed as the product of the MTFs of each part. In general, the MTF at the Nyquist frequency is quantitatively evaluated.

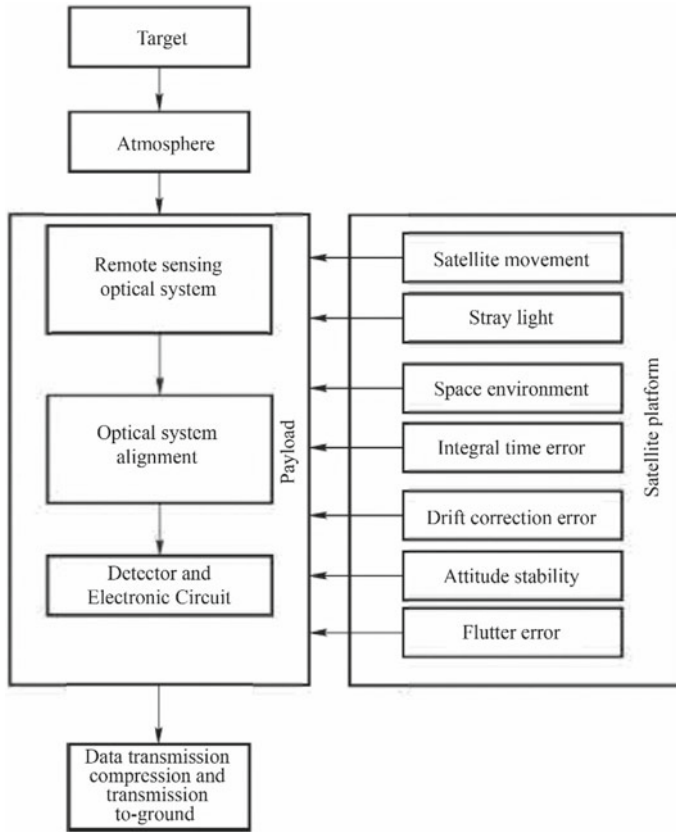


Fig. 3.17 Block diagram of the imaging link system

3.7.5.1 Influence of Atmosphere on On-Orbit Dynamic MTF

Before the radiation reflected by the ground object reaches the remote sensing camera, it passes through the Earth's atmosphere, so the spectral distribution and radiation energy of the ground object have been changed, thus affecting the MTF of satellite on-orbit imaging. Atmospheric MTF is mainly affected by solar altitude angle, detection wavelength, atmospheric visibility, and other factors.

- (1) **The influence of solar elevation angle on MTF of satellite imaging:** The contrast of ground scene will be significantly decreased after passing through the atmosphere. The change factor is related to the solar elevation angle. The lower the solar altitude angle, the greater the contrast drops. For example, under the typical imaging conditions with solar altitude angle of 30° and surface reflectance of 0.2, $MTF_{\text{atmospheric}}$ can generally be taken as 0.8.
- (2) **The influence of the solar elevation angle on the SNR of satellite imaging:** Under the same gain and grade, the SNR of the camera increases with the

increased solar elevation angle and surface reflectance. In other words, the SNR is greatly affected by using the same imaging setting parameters with the same camera in different seasons, and even when using the same imaging setting parameters on the same day, the SNR in low latitudes is higher than that in high latitudes.

- (3) **The influence of atmospheric visibility on the quality of satellite imaging:** Atmospheric visibility reflects the cleanliness of the atmosphere, and the poorer the visibility of the atmosphere, the more turbidity of the atmosphere, which increases the atmospheric scattering influence, thus affecting the final image quality.

Typical 23 km visibility conditions are usually selected for on-orbit dynamic MTF analysis of satellites. The influence coefficient of the atmosphere on the MTF is about 0.81.

3.7.5.2 Camera Static MTF

Camera static MTF includes the MTF product of optical lens, optical alignment, CCD, and electronic circuit. For optical system MTF calculation, refer to Eq. (3.4). Taking an optical system with the average MTF of 0.45 and 0.65 at Nyquist frequency and 1/4 Nyquist frequency, respectively, as an example, assuming that the alignment factor $MTF_{\text{alignment}}$ of optical lens processing is 0.85–0.90, the average MTF_{CCD} of the detector in the spectral range is 0.55–0.57, the influence coefficient of $MTF_{\text{electronic circuit}}$ of electronic circuit is generally 0.95, then the static MTF is calculated as 0.2 for the full chromatographic spectral segmentation and 0.3 for the multispectral segmentation.

3.7.5.3 Influence of Push-Broom on On-Orbit Dynamic MTF

Like a normal linear array, TDI CCD has an inherent descent factor caused by push-broom in flight direction. This MTF reduction factor is calculated as follows:

$$MTF_{\text{push-broom}} = \frac{\sin(\pi v_n d)}{\pi v_n d} = 0.636, \quad (3.14)$$

where v_n is sampling frequency $1/(2p)$ (p is the pixel size); d is the image shift distance in an integral time and the filling factor is 1, i.e., $d = p$.

3.7.5.4 Influence of Integral Time Setting Accuracy on On-Orbit Dynamic MTF

TDI CCD imaging requires synchronization of ground motion and image shift. The influence of integration time setting accuracy on image quality is detailed in Table 3.10. At present, when the accuracy of integration time setting is better than 0.3%, the $MTF_{\text{integration time}} = 0.99$ under the 48th integral grade and $MTF_{\text{integration time}} = 0.97$ under the 96th integral grade.

3.7.5.5 The Influence of Drift Correction Accuracy on On-Orbit Dynamic MTF

Since the visible spectral camera imaging device is a TDI CCD, and the imaging is completed by the principle of time delay integration, the lateral offset caused by the Earth rotation and the drift shall be compensated. The drift for camera imaging shall be controlled by the satellite during the to-ground imaging, and the accuracy of drift correction will affect the imaging performance of the camera, which is mainly manifested in the image shift caused by the drift correction error and the decrease of MTF.

Since the camera adopts the TDI CCD imaging system, it is necessary to compensate the lateral shift caused by the Earth's rotation, that is, the drift is controlled. The accuracy of the drift angle correction directly affects the on-orbit imaging performance of the satellite. The main performance is that the drift angle correction error will cause image shift and MTF degradation. The image shift caused by the drift angle correction error Δd is

$$\Delta d = m \cdot c \cdot \tan(\theta), \quad (3.15)$$

$$MTF_{\text{drift}} = \sin c(\pi v_n \Delta d), \quad (3.16)$$

where m is integral grade, θ is correction accuracy of drift, v_n is sampling frequency $1/(2p)$ (p is pixel size). The relationship of correction accuracy of different drifts with MTF of satellite on-orbit imaging is shown in Table 3.11. At present, the drift correc-

Table 3.11 The relationship between the drift correction accuracy ($\Delta\theta$) and MTF

MTF		Integral grade				
		16	32	48	64	96
$\Delta\theta$	0.03°	1.000	1.000	0.999	0.9982	0.9958
	0.05°	1.000	0.999	0.999	0.9982	0.9958
	0.1°	1.000	0.997	0.9942	0.995	0.989

tion accuracy of remote sensing satellite is better than 0.05° , and the degradation factor of image quality on-orbit is $MTF_{\text{drift}} = 0.99$.

In general, the drift correction accuracy of the high-resolution visible spectral satellite is better than 0.05° , and the resulting imaging quality factor $MTF_{\text{drift}} = 0.99$.

3.7.5.6 The Influence of Attitude Stability on On-Orbit Dynamic MTF

The influence of attitude stability on MTF of the camera is mainly caused by the image shift generated by the multigrade integration of TDI CCD. According to the following equation, the image shift Δd is calculated as follows:

$$\Delta d = \bar{\omega} \cdot f \cdot m \cdot t_i,$$
 (3.17)

where $\bar{\omega}$ is the attitude drift angular velocity, in $^\circ/\text{s}$; f is the focal length; m is integral grade; t_i is integral time.

Therefore, the influence of the low-frequency linear motion of the control system on the MTF is determined by

$$MTF_{\text{attitude stability}} = \sin c(\pi v_n \Delta d),$$
 (3.18)

where v_n is the sampling frequency $1/(2p)$ (p is pixel size).

The influence of satellite attitude stability on the system MTF is shown in Table 3.12. If the attitude stability of the satellite is $5 \times 10^{-4}/\text{s}$, the image shift generated in the period of the camera imaging integration time has little influence on the MTF of the camera imaging, and $MTF_{\text{attitude stability}} = 0.99$. If the attitude stability of the satellite is $2 \times 10^{-3}/\text{s}$, and the integral grade is 96, the influence of the image shift generated in the period of the camera imaging integration time on the MTF of the camera imaging is $MTF_{\text{attitude stability}} = 0.98$.

Table 3.12 Influence factors of satellite attitude stability on MTF

Attitude stability/ $[(^{\circ}) \text{ s}^{-1}]$	MTF influence factor under different TDI CCD integral grade			
	$N = 24$	$N = 36$	$N = 48$	$N = 96$
5×10^{-4}	0.9999	0.999 8	0.9996	0.9984
1×10^{-3}	0.9996	0.9991	0.9984	0.9938
1.5×10^{-3}	0.9991	0.9980	0.9964	0.9860
2×10^{-3}	0.9984	0.9964	0.9938	0.9751

3.7.5.7 Influence of Flutter on Dynamic MTF On-Orbit

During the satellite's on-orbit operation, the vibration with a smaller amplitude and wider frequency domain is usually called flutter. Flutter will cause the optical camera to image not only the same object in the imaging time, which will lead to the degradation of the imaging quality. According to the different ratios of flutter frequency to camera imaging frequency, it can be divided into high-frequency flutter and low-frequency flutter. Generally, the influence of different frequency flutter on image varies greatly.

(1) Influence of low-frequency flutter on on-orbit dynamic MTF (Fig. 3.18).

For low-frequency sinusoidal vibration of a single frequency, the maximum image shift is

$$d_{\max} = 2L \sin \left[\left(\frac{2\pi}{T_0} \right) \left(\frac{T}{2} \right) \right] = 2L \sin(\pi \nu_0 T) \quad (T < T_0/2), \quad (3.19)$$

where ν_0 is the vibration frequency, $\nu_0 = 1/T_0$, T is m -order integration time, $T = m \cdot t_i$, T_0 is vibration period, L is amplitude, and t_x is the starting time of TDI CCD integration.

The calculation equation of the influence of the low-frequency vibration image shift on the image MTF is as follows:

$$\text{MTF}_{\text{low frequency flutter}} = \sin c(\pi \nu_n d_{\max}), \quad (3.20)$$

where ν_n is the sampling frequency $1/(2p)$ (p is pixel size). The influences of different image shifts on image MTF are shown in Table 3.13. For high-resolution optical

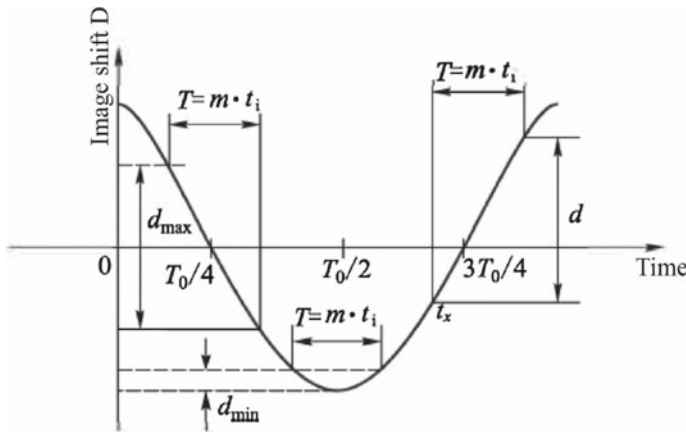


Fig. 3.18 Sketch of low-frequency flutter

Table 3.13 Influence of low-frequency vibration on image MTF

Image shift/pixel	0.1	0.2	0.3	0.4	0.5
MTF	0.996	0.984	0.963	0.935	0.900

remote sensing satellites, the maximum image shift $d_{\max}$ of low-frequency flutter is required to be less than 0.2 pixels, so $\text{MTF}_{\text{low frequency}} = 0.984$.

(2) Influence of High-Frequency Flutter on On-orbit Dynamic Imaging MTF

The flutter is called high-frequency flutter if the vibration frequency f_0 is greater than half of the camera imaging frequency, $f/2$, when the satellite is in a certain operating grade. The calculating equation for the influence of high-frequency flutter on image MTF is as follows:

$$\text{MTF}_{\text{high frequency flutter}} = J_0(2\pi \nu_n L), \tag{3.21}$$

where J_0 is a 0-order Bessel function, ν_n is the sampling frequency $1/(2p)$ (p is the pixel size), and L is the amplitude. The influence of high-frequency flutter on the MTF is shown in Table 3.14. It can be seen that the high-frequency flutter has a great influence on the imaging quality of the system. It is usually required that the relative amplitude of the high-frequency flutter transmitted to the camera image plane is no more than 0.1-pixel size, and the corresponding $\text{MTF}_{\text{high frequency}} = 0.975$. When the pixel size is larger than 0.2, the corresponding $\text{MTF}_{\text{high frequency}} = 0.903$, which has an unacceptable impact on the image quality. In summary, high-frequency flutter’s characteristics, measurement, suppression, and verification are the toughest tasks in the design of a high-resolution remote sensing satellite system.

Therefore, when the amplitude is the same, the influence of high-frequency flutter generated in unit integration time on MTF imaging is much greater than that of low-frequency flutter. In the general design of satellite, the amplitude–frequency characteristics and resonance characteristics of multiple vibration sources on the satellite should be systematically analyzed and controlled. Only by taking effective flutter suppression measures, the camera image shift caused by high-frequency flutter of the whole satellite can be controlled within 0.1 pixels, and the image shift caused by low-frequency flutter within 0.2 pixels. Its influence on MTF is $\text{MTF}_{\text{flutter}} = \text{MTF}_{\text{low-frequency}} \times \text{MTF}_{\text{high-frequency}} = 0.984 \times 0.975 = 0.959$.

Table 3.14 Influence of high-frequency flutter on image MTF

Image motion/pixel	0.1	0.2	0.3	0.4	0.5
MTF	0.975	0.903	0.790	0.646	0.471

3.7.5.8 Influence of Stray Light on On-Orbit Dynamic MTF

The nonimaging beam outside the field of view reaches the image plane after diffuse reflection through the lens barrel, which will cause uneven illumination to the detector, thus reducing the image contrast. For example, if the stray coefficient of the optical system is 3%, the MTF calculated by Eq. (3.10) is degraded as $MTF_{\text{straylight}} = 0.97$.

3.7.5.9 Influence of Camera Structural and Thermal Stability on MTF

Although the imaging performance of the camera system can be validated to a certain extent by the mechanical environment test of the active segment on the ground, the vacuum thermal environment imaging test of the space and the on-orbit weightlessness simulation test of the 180° flip of the camera, considering the difference between the ground test and the actual on-orbit flight environment, the structural and thermal stability of the camera on-orbit still has some influences on MTF. This influence mainly refers to defocusing, which can be solved by on-orbit focusing. The influence of defocusing on the MTF of the camera can be calculated using the following equation:

$$MTF_{\text{defocusing}} = 2J_1(X)/X, \quad (3.22)$$

where J_1 represents the first-order Bessel function, $X = \pi d \nu_n$, d denotes the diameter of the dispersion circle caused by defocusing, $d = \Delta l/F$, Δl is the defocusing amount, F denotes the reciprocal of the relative aperture, and ν_n is the characteristic frequency, i.e., the spatial frequency corresponding to the Nyquist frequency. If the focusing accuracy of the camera is much higher than that of the focal depth, it can be considered that the $MTF_{\text{thermal/mechanical}}$ of the focusing process is 0.99.

3.7.5.10 On-Orbit Dynamic MTF Comprehensive Analysis

(1) On-orbit dynamic MTF analysis

In the general design and engineering development process of satellite, the full-link and full-element modeling of the satellite is analyzed and evaluated for on-orbit dynamic imaging MTF according to satellite system-wide design results and product implementation. Generally, MTF at Nyquist frequency is used as the evaluation criterion to analyze and evaluate the design rationality of the imaging quality parameters and the effectiveness of control measures, so as to ensure that the satellite imaging quality meets the application requirements. The relationship of the on-orbit dynamic MTF of satellite system and the MTF influence factors of each part can be calculated by the following equations:

For system MTF in the flight direction:

$$\begin{aligned}
MTF_{\text{total flight}}(\nu) = & MTF_{\text{atmosphere}} \times MTF_{\text{camera}}(\nu) \times MTF_{\text{push - broom}} \\
& \times MTF_{\text{thermal/mechanical}} \times MTF_{\text{stray light}} \times MTF_{\text{integration time}} \\
& \times MTF_{\text{attitude stability}} \times MTF_{\text{flutter}}, \quad (3.23)
\end{aligned}$$

For system MTF in the vertical direction:

$$\begin{aligned}
MTF_{\text{total vertical}}(\nu) = & MTF_{\text{atmosphere}} \times MTF_{\text{camera}}(\nu) \times MTF_{\text{thermal - mechanical}} \\
& \times MTF_{\text{stray light}} \times MTF_{\text{drift angle}} \times MTF_{\text{attitude stability}} \times MTF_{\text{flutter}}, \quad (3.24)
\end{aligned}$$

The statistical results of satellite MTF on orbit are as follows:

$$MTF_{\text{on-orbit}}(\nu) = [MTF_{\text{total flight}}(\nu) \times MTF_{\text{total vertical}}(\nu)]^{1/2}. \quad (3.25)$$

Since the satellite push-broom motion and the integration time error only cause the degradation of the MTF in the along-track direction, and the drift correction error only causes the degradation of the MTF in the cross-track direction, the MTF in the along-track direction and in the cross-track direction shall be calculated separately. Based on the analysis results of the various processes mentioned above in this chapter, the analysis is performed on the on-orbit common integral grade of no higher than 48. The estimated results are shown in Table 3.15.

(2) On-orbit image influence the prediction of different MTFs

As can be seen from the comparison of Fig. 3.19, the image with a dynamic MTF of 0.07 is poor in contrast, the target edge is blurred, and the internal details are lost.

The image with the dynamic MTF of 0.1 is better in contrast, edge, and detail. Therefore, the on-orbit dynamic MTF of high-resolution optical remote sensing satellites is usually designed to be around 0.1.

3.7.6 On-Orbit Dynamic Range Analysis

The camera on-orbit dynamic range refers to the maximum output amplitude and the resolvable minimum signal amplitude that the imaging system can respond to the input signal in case of unsaturation. The design rationality of dynamic range is directly related to the level, brightness, and contrast of satellite images, and ultimately affects the image quality. The bigger the dynamic range, the more distinguishable the image, and the larger the amount of information, and the better the visual effect of the image will be.

The camera on-orbit dynamic range is mainly affected by on-orbit imaging conditions, TDI CCD characteristics, A/D circuit characteristics, and system parameter settings. The design of camera imaging circuit takes the measures of customizing

Table 3.15 On-orbit dynamic MTF prediction results (integral grade 48, Nyquist frequency 50 Ip/mm)

No.	Influencing factor	Panchromatic		Multispectral	
		Flight direction	Vertical direction	Flight direction	Vertical direction
1	Camera static MTF	0.21	0.21	0.30	0.30
2	Atmosphere	0.81	0.81	0.81	0.81
3	Push-broom motion	0.637	1.000	0.637	1.000
5	Integration time synchronization accuracy	0.990	1.000	0.990	1.000
6	Attitude stability	0.990	0.990	0.990	0.990
7	Correction accuracy of drift	1.000	0.990	1.000	0.990
8	Satellite flutter	0.959	0.959	0.959	0.959
9	Stray light	0.970	0.970	0.970	0.970
10	Thermodynamic environment (including focusing)	0.990	0.990	0.990	0.990
11	Total	0.098	0.153	0.140	0.219
12	Comprehensive consideration of both directions	0.123		0.175	

high-quality TDI CCD and high-speed imaging circuit with noise suppression, the on-orbit imaging parameters are reasonably set according to the on-orbit imaging conditions, illumination characteristics, atmospheric characteristics, and other factors to ensure the dynamic range, thus adapting different on-orbit imaging conditions.

The input dynamic range of an imaging system is usually expressed by the maximum and minimum spectral radiance range of incidence, and depends on the radiance range of the scene and object in the target area of interest. According to the statistics of the Earth's illumination conditions, for the region whose solar elevation angle is less than 70° in the 80° north and south global latitude range, the typical target reflectance is ranged mainly between 0.05 and 0.50 according to the statistics of the target reflectivity characteristic system. Therefore, the ground input conditions of the camera shall be adapted to the range: the maximum input is at the sun's elevation angle of 70°, and the ground reflectance is 0.50; the minimum input is at the solar elevation angle of 20°, and the ground reflectance is 0.05. The input dynamic range has the following characteristics:

- (1) The input dynamic range depends on the equivalent spectral radiance range of the target. For the orbit with the same descending node local time, the equivalent spectral radiance at the same latitude in the same season is the same.



Fig. 3.19 Comparison image with 0.1 MTF with an image with 0.07 MTF

- (2) The input dynamic range is independent of the orbital height, nonlinear with the solar elevation angle, and linear with the target reflectivity;
- (3) The input dynamic range of $(70^\circ, 0.50)$ to $(20^\circ, 0.05)$ meets the requirements of high-resolution visible spectral remote sensing data acquisition.

The output dynamic range is generally expressed by the voltage with linear or monotonic variation to system response or gray value range. Under the same imaging condition, i.e., the same gain, integral grade and integral time, the gray value of the camera should be close to saturation under the condition of maximum input radiance, the gray level should be as low as possible on the premise of ensuring the SNR under the condition of minimum input radiance, thereby improving the camera dynamic range and the level and contrast of the satellite image.

If the camera is calculated as a linear system under the same operating grade and gain, it is difficult to ensure that the output gray value of the camera is greater than or equal to 80% of the full range, while the output corresponding to the low input condition of the dynamic range is less than or equal to 2% of the full range. Therefore, the response curve of the camera shall be designed as a negative intercept linear system. The grade and gain of the camera are adjusted according to the target conditions of the imaging object, so as to ensure that the output dynamic range of the camera meets the requirements. The main measures to improve the dynamic range are as follows:

- (1) **Select and use detector with high-dynamic range:** Assuming that the equivalent input noise of the circuit is about 3 mV and the saturation voltage of the

detector is 2000 mV under the lowest imaging condition, the TDI CCD detector with dynamic range ($\geq 2000/3 = 667$) should be selected.

- (2) **Reasonable selection of quantization bit to improve detail resolution:** At present, the number of quantization bit of visible spectral remote sensing camera is generally 10 bits (output DN value range 0–1023)–12 bits (output DN value range 0–4095). A large number of quantization bit is advantageous for achieving a high output dynamic range. If the noise voltage exceeds the resolution ability of image quantization, increasing quantization bit can no longer improve the quantization hierarchy of image effective signal, and will bring unnecessary burden to data processing and data transmission. Therefore, the selection of quantization bit shall be determined by a comprehensive analysis of various factors. For details see Sect. 3.4.13.
- (3) **Dark-level clamping, make full use of quantization range:** The image background caused by camera circuit pedestal voltage, atmospheric scattering, and stray light can be removed through digital image background subtraction and gray stretch processing, so that the gray distribution can be as full as possible of the whole quantization range of the camera, as detailed in Sect. 3.4.13.
- (4) **Reasonable allocation of integral grade and gain to reduce the influence of atmospheric scattering on the image dark background:** The most direct reflection of atmospheric background on satellite images is that there are image backgrounds in the image unrelated to the ground object. The digital images of remote sensing satellite can be represented by Digital Number (DN). The size of the image background directly affects the effective range of the ground object information in the image. The larger the image background, the narrower the effective range of the object information, and the more compressed the gray level of the image information. The lower the reflectance of ground objects and the solar elevation angle, the more severe the dynamic range of atmospheric occupancy. In order to reduce the influence of the atmosphere on the dynamic range, the intensity of the imaging signal shall be improved and the proportion of the atmospheric background in the image shall be reduced by adjusting the integral grade and gain of the camera on-orbit.

3.7.7 On-Orbit SNR Analysis

SNR depends primarily on signal and noise power. The signal power is mainly related to imaging conditions such as illumination conditions and target spectral reflectance, as well as relative aperture of the camera, optical efficiency, and photo-electric characteristics of the TDI CCD. The noise power is mainly related to the noise characteristics of the detector and its electronic circuit.

3.7.7.1 On-Orbit SNR Estimation

The estimation method of on-orbit SNR of a camera is to use the software “6S” and MODTRAN to analyze apparent radiance under specific conditions; to calculate the equivalent radiance of the object spectrum in the response spectrum of the camera by using the spectral information of the camera and the responsibility information of the detector; to calculate the output DN value of the signal based on the optical system design and the design parameters of the imaging electronic system; and to determine the corresponding DN value of the noise according to the design parameters of the camera imaging electronic system, then the SNR is estimated based on the signal and noise.

(1) Apparent radiance calculation

Taking typical summer atmospheric conditions as an example, the apparent radiance of the camera is calculated. The input parameters include the orbital altitude of 500 km; the azimuth of the sun, the zenith angle of the satellite, and the azimuth angle of the satellite are selected as 0; the observation date is June 23; the atmospheric model is a mid-latitude summer model; the aerosol type is a continental type; and the atmospheric visibility spectrum is 23 km; the spectral range is 0.5–0.8 μm. The calculated results are shown in Table 3.16.

(2) Equivalent apparent radiance calculation

The equivalent apparent radiance of the ground object spectrum in the camera response spectrum band is calculated according to the following formula:

$$L = \frac{\int_{\lambda_1}^{\lambda_2} L(\lambda) \times R(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} LR(\lambda) d\lambda}, \tag{3.26}$$

where L is the equivalent spectral apparent radiance in the spectral range $\lambda_1 \sim \lambda_2$, $L(\lambda)$ is the spectral apparent radiance in the spectral range, and $R(\lambda)$ is the normalized spectral responsivity of the camera in the spectral range.

Table 3.16 The camera apparent radiance data in the summer by imaging at the sub-satellite point, in W/(m² sr μm)

Ground object reflectivity/%	Solar elevation angle/(°)				
	10	20	30	50	70
5	9.617	15.343	19.815	27.565	33.492
20	15.470	30.989	45.611	70.984	88.492
40	23.554	52.605	81.255	130.989	164.504
60	31.978	75.138	118.417	193.560	243.772
70	36.325	86.768	137.601	225.865	284.699

(3) TDI CCD output voltage and A/D quantization output bit calculation

The camera TDI CCD voltage output is calculated according to the spectral response curve of the TDI CCD, and the output bit value of the camera after A/D conversion is calculated according to the setting conditions of the electronic gain amplification factor of the camera and the characteristics of the A/D device.

$$V_{\text{ccd}} = m \cdot t \cdot \frac{\pi}{4} \cdot \left(\frac{D}{f}\right)^2 \cdot (1 - \beta) \cdot T_e \cdot \int_{\lambda_1}^{\lambda_2} L_p(\lambda) \cdot R(\lambda) \cdot d\lambda, \quad (3.25)$$

$$\text{DN} = V_{\text{ccd}} \cdot G \cdot \eta_{\text{AD}}, \quad (3.26)$$

where m is the optional integral grade of CCD; t_i is the exposure time in the first integration process; $\frac{D}{f}$ is the relative aperture of the optical system; β is the surface occlusion coefficient of the camera; T_e is the equivalent spectral transmittance of the optical system; $L_p(\lambda)$ is the pre-pupil spectral radiance; $R(\lambda)$ is the normalized spectral responsibility of the CCD; G is the basic gain magnification of the CCD circuit. η_{AD} is an A/D conversion coefficient, which is related to the quantization bit and the maximum output saturation voltage of TDI CCD device. If the saturation voltage is 2 V and the quantization bit is 10 bits, the A/D conversion coefficient is $2^{10}/2$.

(4) Noise Estimation

For details, see Sect. 3.4.13.

(5) SNR calculation

According to the camera signal and noise estimation results, the following equation is used to determine the SNR:

$$\text{SNR} = 20 \log \frac{S}{N}, \quad (3.27)$$

where S is the signal DN value and N is the noise DN value.

3.7.7.2 Improvement of Camera On-Orbit SNR Design Measures

The main measures to improve the SNR of satellite on-orbit imaging are as follows:

- improve the surface reflectivity of the optical mirror ($\geq 96\%$) to reduce the loss of light energy from the apparent radiance to the exposure at the focal plane;
- select the TDI CCD with full well charge capacity to improve the SNR, because the SNR of TDI CCD is proportional to the square root of the full well charge capacity;

- (c) increase TDI CCD integral grade according to on-orbit imaging conditions to improve the signal intensity;
- (d) reduce TDI CCD operating temperature to reduce its dark current noise;
- (e) reduce the total noise of imaging circuit by selecting high-performance, low-noise video processing chip, and EMC noise suppression design of high-speed imaging circuit.

3.8 Geometric Positioning Accuracy Analysis

3.8.1 Error Source Analysis

Image positioning accuracy, a satellite ground integration index, refers to the ground application system systematically correcting the image geometric, eliminating various systematic errors caused by satellite attitude motion and push-broom imaging motion, and root mean square error of target position of the corrected image by using satellite orbit data and attitude data. The satellite positioning accuracy is evaluated on the basis of performing internal and external calibration, and removing system errors. Figure 3.20 depicts the analysis of the influencing factors of geometric positioning accuracy.

Relative positioning accuracy (also known as internal geometric accuracy) is an evaluation of the consistency between the absolute amount of internal geometric deformation (such as length, angle, and radiation deformation) and that of the whole image. For remote sensing satellites with linear array push-broom imaging system, its relative positioning accuracy is mainly affected by the instability error of the azimuth elements in the camera and the stability of the angle/line elements in the imaging after satellite attitude maneuver, which is mainly affected by the camera's internal azimuth element in cross-track direction; in the along-track direction, it is also affected by both the camera's internal azimuth element's on-orbit instability and the external azimuth factors, such as attitude measurement accuracy, stability and high-frequency flutter after attitude maneuver.

Absolute positioning accuracy, also known as external geometric accuracy, refers to the deviation between the coordinate positions of multiple reference targets selected from the geometrically corrected remote sensing images and their actual positions, i.e., the difference between the geographical positions of image points on the image and the real geographic positions. Absolute positioning accuracy is affected by both internal and external azimuth elements, and the influencing factors are more complicated, including on-orbit instability error of camera internal azimuth elements, orbit determination error, time synchronization accuracy, attitude sensor measurement error, satellite attitude determination error and stability, satellite high-frequency flutter, instability error of camera-to-star tracker optical axis angle, and the calibration residual of the ground system. Especially, the orbit accuracy of the

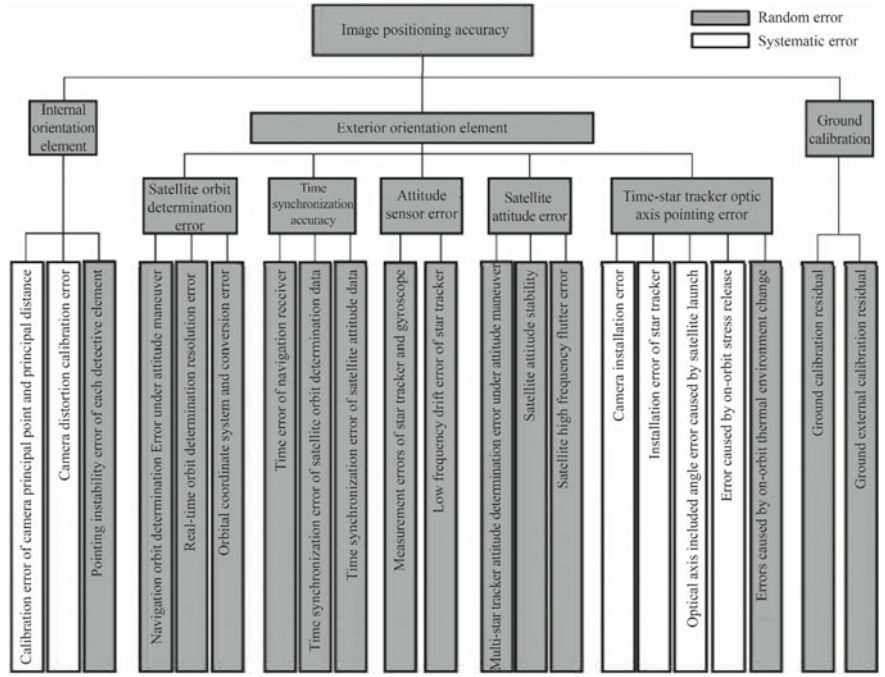


Fig. 3.20 Analysis of factors affecting geometric positioning accuracy

navigation receiver and the attitude measurement accuracy of the star tracker will decrease by the satellite maneuvering at a large angle.

3.8.2 Design Measures for Improving Positioning Accuracy

With the development of remote sensing satellite technology, the positioning accuracy of high-resolution visible spectral remote sensing satellite is getting higher and higher. The absolute positioning accuracy of the satellite has been improved from the initial 100 m magnitude to less than 10 m. However, the improvement of satellite agile imaging capability brings new challenges to the guarantee of image geometric positioning accuracy.

Key measures to achieve high geometric positioning accuracy include the following:

- (1) Very-high-precision, high-dynamic star tracker is equipped to ensure high-precision original attitude measurement data of the dual-star tracker in various agile maneuver imaging modes.
- (2) On-board high-precision star trackers, gyroscopes, and other attitude measurement components are integrated with the camera and carried out high-precision

temperature control, in order to reduce the accuracy transfer parts and instability, and eliminate the fixed deviation through on-orbit calibration.

- (3) High-precision navigation receiver is used to record downloaded real-time orbit measurement data together with high-precision unified reference source and GPS second pulse. The on-board high-precision time synchronization is established to realize time synchronization accuracy of all relevant data sources better than 100 μ s.
- (4) To improve the positioning accuracy of the system, a variety of high-precision joint attitude determination methods are developed, including high-precision star camera, high-frequency angular displacement sensor, as well as the original image and gyroscope data of the star camera to solve the impact of star tracker accuracy on attitude maneuver imaging.

3.8.3 Joint Attitude Determination Method and Accuracy Analysis

Attitude measurement accuracy is the most important and weighted factor in positioning accuracy. By using a variety of attitude measurement equipment, a high-resolution visible spectral remote sensing system achieves joint attitude determination with higher accuracy and measurement frequency to determine the attitude information of each line as accurately as possible. Among them, star tracker/camera provides absolute attitude measurement data; high-precision three-float gyroscope, fiber optic gyroscope, and high-precision angular displacement device provide relative attitude measurement data with higher measurement frequency, usually angular rate or angular increment. Next, several joint attitude determination modes are discussed and their accuracy is analyzed.

3.8.3.1 On-Board Joint Attitude Determination Mode

The satellite control subsystem determines attitude by the combination of star tracker and gyroscope, and then inputs the star-sensitive quaternion into auxiliary data. The attitude determination accuracy can reach 0.001° when the attitude is jointly determined by the dual-star trackers. This attitude determination method is convenient for ground application, fast processing of image data, and geometric positioning processing.

3.8.3.2 Accuracy Analysis of Attitude Determination Based on Original Multi-Star Tracker Q-Value

Satellite usually uses three very-high-precision star trackers as the main attitude measurement components, which are all in operation state on-orbit. The angle

between star trackers should be maintained at 90° as far as possible. Under normal circumstances, on-orbit joint attitude determination is usually carried out by introducing two star trackers out of three. However, in special cases such as specific sky areas and star tracker irradiated by sunshine/moon light, the attitude determination can also be carried out by introducing one single-star tracker out of three. The optical axis measurement accuracy of star tracker is α , the transverse axis measurement accuracy is β , and the angle between two star trackers is φ . Without considering the influence of the low frequency or short period term of star tracker, the attitude determination accuracy of star tracker is calculated as follows:

- (1) For single-star tracker attitude determination, with the accuracy of very-high-precision star tracker optical axis measurement α of better than $1''(3\sigma)$, and the accuracy of transverse axis measurement β of better than $30''(3\sigma)$, the synthetic error of single-star tracker attitude measurement is

$$m_{x \text{ star tracker}} = m_{y \text{ star tracker}} = \sqrt{\alpha^2 + \beta^2} = \sqrt{1^2 + 30^2} = 30.02''(3\sigma), \quad (3.30)$$

It can be seen that the accuracy of single-star tracker attitude determination is poor. Therefore, it is necessary to configure at least two star trackers in order to achieve high-precision attitude measurement.

- (2) For the case of dual-star tracker attitude determination, the measurement error of dual-star tracker attitude determination is calculated as follows:

$$m_{x \text{ star sensitivity}} = m_{y \text{ star sensitivity}} = \sqrt{m_1^2 + m_2^2 + m_3^2}, \quad (3.31)$$

where m_1 is the bisector accuracy of the angle between two star trackers, which is determined by Eq. (3.34); m_2 is the vertical direction accuracy of the bisector of the angle between two star trackers in the plane of dual-star tracker optical axis, which is determined by Eq. (3.33); m_3 is the direction accuracy of the vertical dual-star tracker optical axis, which is determined by Eq. (3.34).

$$m_1 = a \times \frac{1}{\cos(\varphi/2)} \times \frac{\sqrt{2}}{2}, \quad (3.32)$$

$$m_2 = a \times \frac{1}{\cos(90 - \varphi/2)} \times \frac{\sqrt{2}}{2}, \quad (3.33)$$

$$m_3 = a \times \sqrt{1 + \frac{1}{\sin^2 \varphi}}. \quad (3.34)$$

The accuracy of dual-star tracker attitude determination depends on the angle between the dual-star tracker optical axis. Therefore, in order to achieve high-precision attitude measurement and determination, it is necessary to ensure that the angle between the star tracker optical axis is larger than a certain angle.

3.8.3.3 Analysis of the Influence of Low-Frequency Error of Star Tracker

The low-frequency error of star tracker mainly includes two parts: field of view space error and thermal distortion error. The field of view spatial error refers to the error component that the with-star-point moves slowly in the field of view. Its influence ranges from several pixels to the whole image plane. The low-frequency error variation period usually ranges from tens of seconds to an orbit period, which is composed of optical system calibration residual, optical system chromatic aberration distortion, star catalogue error, etc. The thermal deformation errors are caused by the changes of thermal environment of star tracker, including the influence of sunshine and shadow of Earth, the power consumption changes caused by the switch of refrigerator, the temperature and temperature gradient of installation surface, and the thermal control action of thermal control system. It is generally characterized by periodic changes on-orbit and is a low-frequency random error in the time domain.

3.9 Spectral Registration Analysis

The accuracy of spectral registration is an important index for evaluating the quality of multispectral images, which determines the influence of its subsequent application. Usually, the camera design needs to place CCD arrays according to the strict geometric relationship required by inter-spectral band registration to ensure the registration accuracy. However, due to installation errors and optical distortion of lens between different spectral bands, the registration accuracy between spectral segments shall be improved by post-processing technology on the ground after satellite imaging on orbit.

The detector manufacturing and installation accuracy is a fixed error, which can be eliminated by ground system processing. The errors caused by the satellite system, which cannot be eliminated by image registration accuracy mainly come from three aspects: optical system distortion, satellite attitude control accuracy, as well as ground elevation and terrain fluctuation.

3.9.1 Optical System Distortion Stability

Similar to geometric distortion, the influence of inherent distortion of the optical system on registration accuracy can be corrected by on-orbit calibration and precise measurement in the laboratory. The influence of optical distortion stability on registration accuracy is also reflected as the stability of registration accuracy. For high-resolution visible spectral cameras, the stability of the relative distortion for different spectrums at the edge of field of view is usually submicron, with little influence.

3.9.2 Influence of Satellite Attitude Control Accuracy

Factors such as satellite attitude stability and correction of drift will also affect the registration accuracy. In the calculation and analysis, panchromatic, and multispectral registration deviation induced by satellite attitude stability and drift correction error during star tracker's sampling period are calculated by using the design or measurement data of the spacing between the full-spectrum band and multispectral band. For example, assuming that the satellite attitude stability is $5 \times 10^{-4}^\circ/\text{s}$, the correction error of drift is 0.05° , the distance between the panchromatic and multispectral spectral bands of the detector is 5.8 mm, the camera focal length is 10 m, the star tracker's sampling period is 125 ms, the panchromatic pixel size is $10 \mu\text{m}$, and the multispectral pixel size is $40 \mu\text{m}$, then the registration error induced by the attitude stability is about 0.1 multispectral pixels, the registration deviation between panchromatic and multispectral bands induced by drift is about 0.2 multispectral pixels. The maximum registration deviation determined by the characteristics of the satellite platform is 0.22 multispectral pixels under the comprehensive consideration.

3.9.3 Registration Error Induced by Ground Elevation

Because there is a certain distance between the spectral segments of the camera focal plane and the spectral segments are arranged in front and back, when image registration is performed on the ground, the registration error is often caused by the error of elevation information. Figure 3.21 is a cross-sectional image perpendicular to the CCD linear array during push-broom imaging. The angle between ray A and the vertical line is θ , and that between ray B and the vertical line is δ_θ .

In Fig. 3.21, h_1 , h_2 , respectively, represent the elevation difference of the projection point of the ray from P and B1 spectral segments, and the aberration ΔY (object space distance) generated by the terrain fluctuation is

$$\Delta Y = h_2 \tan \theta - h_1 \tan \delta_\theta. \quad (3.35)$$

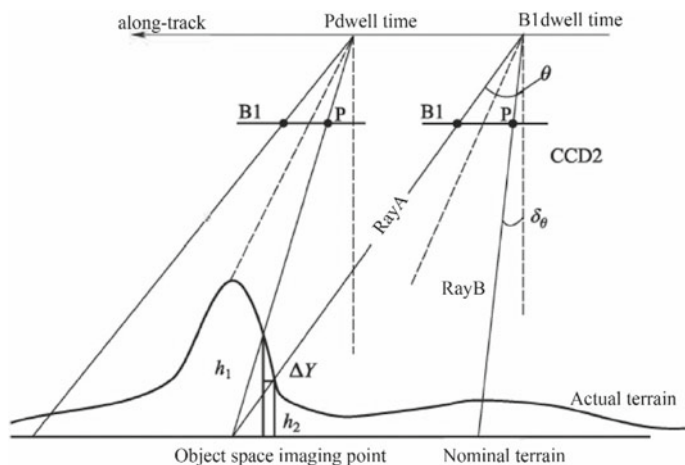


Fig. 3.21 Aberration in along-track direction caused by elevation error

Since ΔY is usually small, $h_1 \approx h_2$, the larger the difference in the viewing angle of the spectral segment installation, the greater the influence of the elevation error on the registration accuracy. If a DEM with an elevation accuracy of about 30 m is used in the ground processing, the orbital aberration is about 0.02 multispectral pixels.

3.10 Laboratory Calibration Technology

3.10.1 Ground Laboratory Calibration

In order to improve the absolute response accuracy of satellites, it is necessary to carry out radiometric calibration of satellites and perform image correction according to the calibration parameters. Relative radiometric calibration in the laboratory mainly includes the consistency adjustment of radiation response between CCDs or channels, the acquisition of relative calibration coefficients given by pixels for relative radiometric calibration, and the relationship between radiation response of calibrated camera and line frequency, gain, and integral grade. The laboratory radiometric calibration process is shown in Fig. 3.22.

The main measures to improve the accuracy of laboratory radiometric calibration include building large-aperture and high-stability integral sphere light source to ensure that the whole aperture and field of view of the large-aperture camera can be fully filled by the integral sphere light source; applying high reflection coating on the inner wall of the integrating sphere to ensure the uniformity of the emitted light angle of the calibration source; using a high-stability power supply to ensure radiance stability of the calibration source; calibrating radiometer with standard

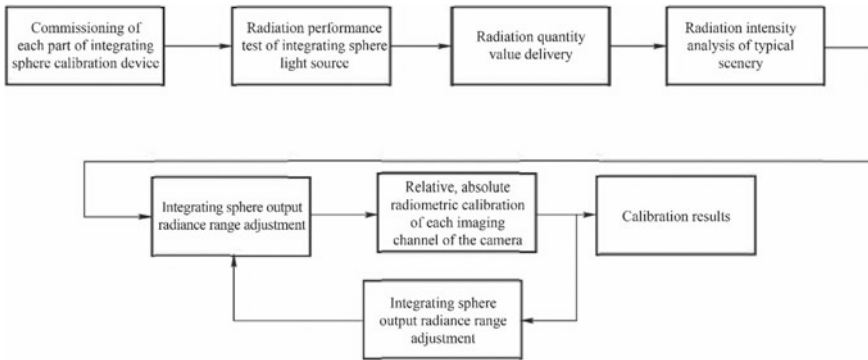


Fig. 3.22 Laboratory radiation calibration experimental procedure

spectral irradiance lamp and standard diffuse reflectance whiteboard calibrated by national metrology department; controlling spectral radiation intensity and output wavelength of the calibrated light source, testing and calibrating relative spectral radiation response of multispectral band of camera.

Due to the influence of the field of view angle of optical system, the pixel response inconsistency of CCD device, and the subsequent processing circuit, different pixels of the same linear array have different response outputs (DN values) under the same gain and radiance. Thus, it is necessary to correct the output of the camera to achieve the same DN output of each pixel at different radiance. Examples of factors affecting relative radiometric calibration accuracy are given in Table 3.17.

According to the error analysis method in China National Military Standard “Radiometric Calibration Method for Space-borne CCD Camera Laboratory,” an example of error source analysis for absolute calibration of satellite cameras is shown in Table 3.18. The absolute calibration error is estimated by Root Mean Square (RMS) of the error sources in the table.

3.10.2 Laboratory High-precision Geometric Internal Calibration

Laboratory precision calibration of camera interior azimuth elements is an important means to ensure high accuracy of camera interior azimuth elements. The calibration schemes of principal points, principal distances, and distortions of camera interior azimuth elements are usually as follows: first detect with precision angle measurement method using optical platform, grid plate, and high-precision Leica theodolite; then test camera inner azimuth elements and distortions using the air-floating platform, high-precision two-dimensional turntable, and light tube with 10 μm star hole.

Table 3.17 Relative calibration error sources and its accuracy analysis

No.	Error source	Error source attribute	Characteristic	Reference value/%
σ_1	Integrating sphere radiometric calibration source surface uniformity (peak-to-valley value)	Test equipment	System	1.5
σ_2	Integrating sphere radiometric calibration source radiance stability	Test equipment	Random	0.5
σ_3	Integrating sphere radiometric calibration source angle uniformity	Test equipment	Random	1.0
σ_4	Camera detector pixel response stability	Camera	Random	1.0
σ_5	Maximum repeatability error of all channels of the camera (camera processing circuit stability)	Camera	Random	1.5
σ_6	Quantization error	Camera	Random	0.5
σ_7	System nonlinearity error (maximum nonlinearity error of camera output signal)	Camera	Random	1.0
σ_8	Calibration algorithm error (corrected image maximum residual)	Camera	Random	1.0
Comprehensive (RMS)				2.55

A grid plate is placed on the image plane of the optical lens to be measured, and a theodolite is used as a measuring telescope to observe the grid plate. The field of view corresponding to the position of the corresponding image plane on the grid plate is measured. Then the distortion parameters of the optical system are obtained by fitting the observed image relationship. The error sources and control measures mainly include the following aspects: the grid plate is precisely carved by photolithographic machine to ensure that the limit error of any distance between reticules is less than $\pm 1 \mu\text{m}$; the inclination error introduced by the installation accuracy of the grid plate is not more than $5''$, which can be neglected; and the measurement error of theodolite is about $\pm 1''$.

Table 3.18 Absolute calibration error sources and its accuracy analysis

No.	Error source	Error source attribute	Characteristic	Reference value/%
$\sigma 1$	Integral sphere radiance calibration	Test equipment	System	5.0
$\sigma 2$	Transfer process	Test equipment	System	3.0
$\sigma 3$	Radiometric calibration source surface (integrating sphere) uniformity (peak-to-valley value)	Test equipment	Random	1.5
$\sigma 4$	Radiometric calibration source (integrating sphere) radiance stability	Test equipment	Random	0.5
$\sigma 5$	Radiometric calibration (integrating sphere) source angle uniformity	Test equipment	Random	1.0
$\sigma 6$	Camera detector pixel response stability	Camera	Random	1.0
$\sigma 7$	Maximum repeatability error of all channels of the camera (camera processing circuit stability)	Camera	Random	1.5
$\sigma 8$	Quantization error	Camera	Random	0.5
$\sigma 9$	System nonlinearity error (maximum nonlinearity error of camera output signal)	Camera	Random	1.0
$\sigma 10$	Camera out-band response	Camera	System	1.0
$\sigma 11$	Out-of-field stray light of camera	Camera	Random	2.0
$\sigma 12$	Calibration algorithm error (maximum residual of corrected image)	Ground	System	1.0
Comprehensive (RMS)				6.7

3.11 Application of Visible Spectral Remote Sensing Satellite

The advent of high-resolution visible light remote sensing satellite at the sub-meter level has opened up a new “vision” for remote sensing applications, making the creation of “digital Earth” and shaping the “digital era” a vision of human social development. High-resolution visible light remote sensing data is used more widely

and intensively in various industries, such as traditional land, surveying, urban construction, national defense, water conservancy, marine, agriculture, forestry, transportation, communications, mining, petroleum, and further expands into new industrial fields such as the internet, navigation and positioning, and wireless communication.

3.11.1 Application of Urban Planning Monitoring

Cities are the environmental basis of human existence, a complex ecosystem that includes society, economy, and nature. Excessive urban development will lead to the intensification of conflicts between human and land, and deteriorate the land resources and ecological environment. High-resolution remote sensing satellite images such as WorldView have the advantages of high spatial resolution, large amount of spatial information and the more obvious characteristics of the ground spectrum, which provide favorable conditions for the fine classification of ground objects and make them widely used in dynamic monitoring and thematic information extraction of urban development. Urban land cover change monitoring based on high-resolution remote sensing has become one of the most important projects in urban ecological environment impact analysis and national geographic condition monitoring. Figure 3.23 gives a schematic diagram of ground objects classification in a city using WorldView-2 satellite imagery.

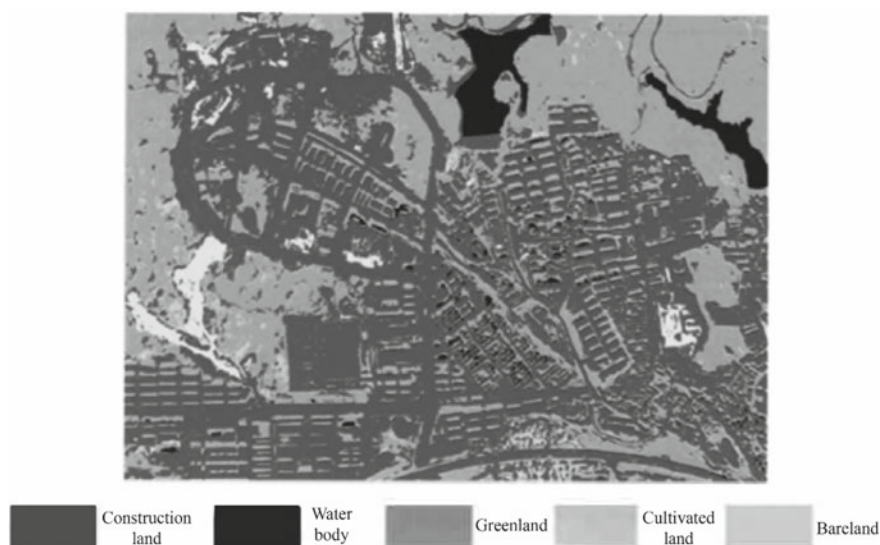


Fig. 3.23 Ground objects classification map of a city using WorldView-2 satellite images

3.11.2 Disaster Prevention and Mitigation Application

After the occurrence of major natural disasters, traffic and communication facilities are usually interrupted in the disaster area. At this time, high-resolution visible spectral remote sensing satellite can quickly and extensively acquire disaster information and master all disaster situations in the disaster area. Under the guidance of prior knowledge of experts, monitoring and evaluation of damaged physical quantities, such as houses, lifelines, infrastructure, land resources, as well as landslides and debris flows, are carried out with multiple anomaly information extraction methods such as automatic interpretation, semiautomatic interpretation, and manual interpretation. For example, high-resolution visible spectral remote sensing satellite data have played an important role in China emergency rescue, disaster loss assessment, and post-disaster reconstruction of Wenchuan earthquake, Yushu earthquake, Zhouqu debris flow, Gongshan debris flow disaster in Yunnan, Guanling landslide, Ankang landslide, Fuzhou flood disaster, Xiangfen dam break, etc. Figures 3.24, 3.25, and 3.26 show the interpretation symbols and characteristics of high-resolution remote sensing satellite images with different degrees of housing damage.

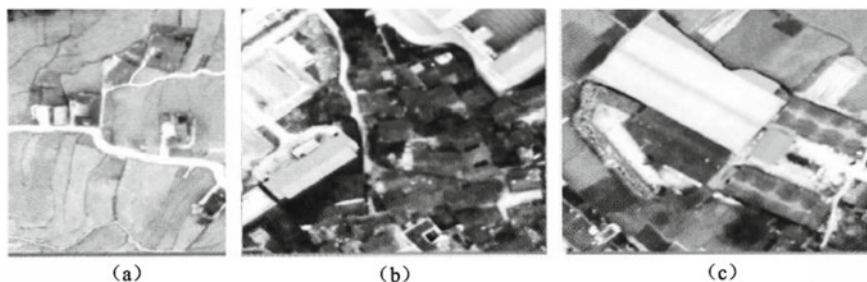


Fig. 3.24 Remote sensing interpretation symbols for house use **a** Rural residential housing; **b** Urban residential housing; **c** Factory buildings

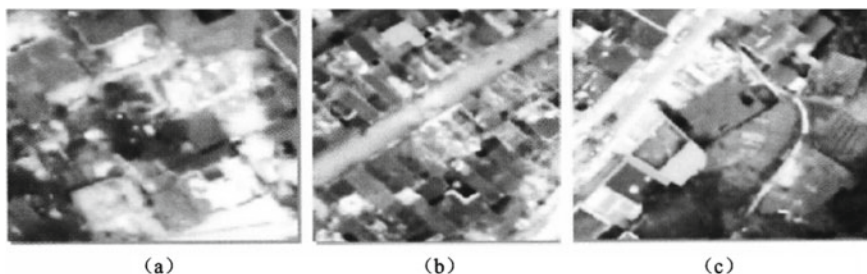


Fig. 3.25 Remote sensing interpretation symbols of the brick and wood buildings damage degree **a** complete collapse; **b** severe damage; **c** general damage

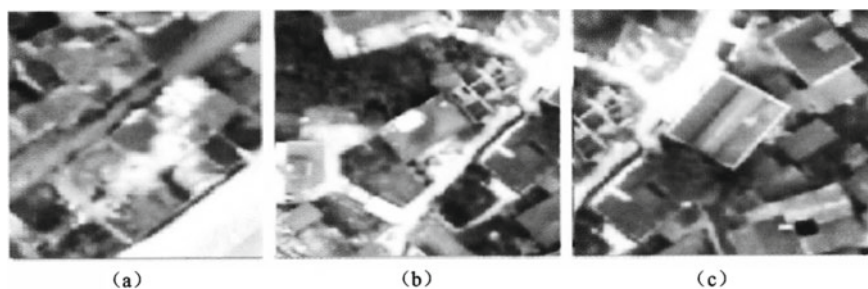


Fig. 3.26 Remote sensing interpretation symbols of the brick-concrete buildings damage degree **a** complete collapse; **b** severe damage; **c** general damage

3.11.3 Road Network Extraction and Monitoring Application

As an essential part of transportation facilities, road network is the basic data of geographic information database. Accurate and actual road network information has a wide range of social needs and plays an important role in social and economic activities. It has been widely used by the public such as vehicle navigation, urban planning management, logistics distribution. The high-resolution visible spectral remote sensing satellite with wide coverage and high-resolution can quickly and effectively detect and extract road target features as the basic geographic information data, which is convenient for updating and application of GIS database, and has very important application prospects. Figure 3.27 shows the detection results of a local road network using QuickBird 0.6 m resolution image.

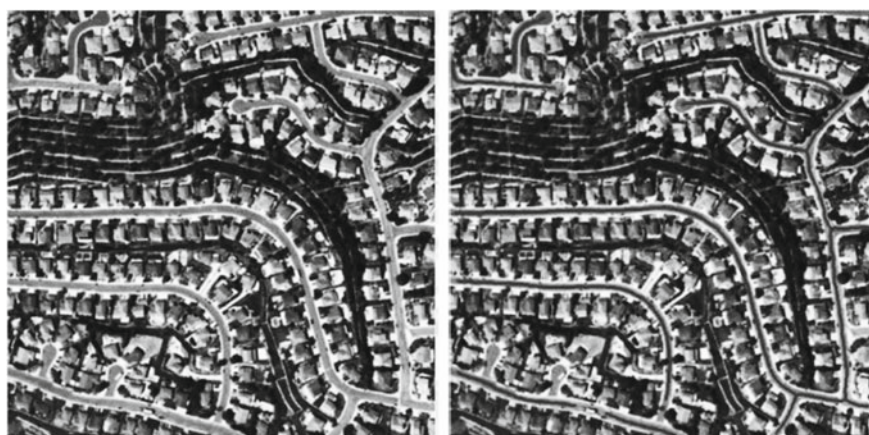


Fig. 3.27 Detection results of road network using satellite QuickBird

3.12 Conclusion

Historically, the spatial resolution of remote sensing satellites has been continuously improved since the launch of the first remote sensing satellite. At present, the optical imaging resolution of commercial high-resolution remote sensing satellites has reached 0.3 m. With the rapid development of optical imaging technology and high-sensitivity photoelectric sensors, the resolution of 0.1–0.3 m or higher can be achieved in the near future. Visible panchromatic + multispectral mode has become the dominant application mode. For example, China's satellite GF-2 is equipped with a full panchromatic band (450–900 nm) and four multispectral bands (450–520, 520–590, 630–690, and 770–890 nm), while Gaojing-1 is equipped with full panchromatic band (450–900 nm) and four multispectral bands (450–890, 520–590, 630–690, and 770–890 nm). The ability to acquire information has been greatly enhanced and the application scope has been further broadened. With the continuous improvement of spatial resolution, imaging quality has put forward higher requirements for satellite attitude control accuracy and drift compensation accuracy. It is necessary to develop attitude control technology with higher accuracy, better stability, and greater maneuverability, that is, develop the “three-super” (super-precision, super-stability, and super-maneuverability) platform technology and the large torque control moment gyro and other actuators to achieve fast attitude maneuverability of $25^\circ/10\text{ s}$ with a stability of better than $1.0 \times 10^{-6}/\text{s}$ (3σ), which will significantly improve the quality, efficiency, and performance of on-orbit imaging.

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Chapter 4

Design and Analysis of Infrared Remote Sensing Satellite System



4.1 Overview

Space infrared remote sensing technology is widely used in many fields such as land and resource, ocean, surveying and mapping, agriculture, forestry, water conservancy, environmental protection, meteorology, disaster reduction, earthquake, and national defense, especially in water pollution monitoring, urban infrared remote sensing and national security and national defense applications. Space infrared remote sensing technology usually refers to the acquisition technology of thermal radiation information of the interested targets through infrared remote sensing instruments or sensors on a space platform (satellite, space station, etc.).

Combining with the development and application experience of resource infrared remote sensing satellite in China, this chapter focuses on the application requirements, technical characteristics and overall design methods of the space infrared remote sensing satellite system, including the overall design elements, on-orbit dynamic imaging quality design and analysis, simulation and experimental verification, infrared radiation calibration, etc.

4.1.1 Development Trend

Infrared remote sensing has an irreplaceable role with visible light, SAR and other remote sensing methods. Infrared remote sensing technology has very broad development prospects. The main development directions are:

- (1) **Higher Resolution Infrared Remote Sensing Technology:** The high-resolution infrared remote sensing has great demand in urban construction, pollution monitoring, disaster prevention and mitigation, national defense construction, and so on. So it also is the main development trend of infrared remote sensing.

- (2) **High-Sensitivity Infrared Remote Sensing Technology:** With its high-temperature resolution, infrared remote sensing system can achieve many functions, such as ecological environment monitoring, air pollution monitoring, mineral exploration, geological hazard investigation, and underwater target detection and recognition. From this perspective, the improvement of temperature sensitivity is also one of the main development directions for infrared remote sensing method. For example, quantum well detectors have a temperature sensitivity of magnitude of mK and good consistency. But they must work at about 40 K temperature to reduce the influence of thermal noise and dark current. The quantum well detector used in Landsat 8, which is launched by the United States in 2013, operates at 40 K, and the detection sensitivity increased to 30 mK.
- (3) **Visible Light/Infrared Multispectral Integrated Remote Sensing Technology:** Unlike visible light remote sensing, although infrared remote sensing can acquire the temperature information of the target, there is a big gap between the recognition of the detailed and geometric characteristics of the target and visible light, so visible light and infrared integrated remote sensing are the main direction of infrared development, and visible light/infrared common aperture integrated camera is the main target of payload development.

4.2 Demand Analysis and Mission Technical Characteristics

4.2.1 Demand Analysis

4.2.1.1 Demand for Infrared Remote Sensing in Land and Resources Exploration

In mineral exploration, infrared band is the spectrum range of spectral characteristics caused by fundamental frequency vibration of minerals. For example, ASTER, WorldView-3, and other payloads have all set up several infrared spectral bands for mineral exploration. In addition, the decay heat of radioactive elements in rocks is an important component of the heat source in the crust, and uranium mineralization causes a large amount of uranium radioactive elements to be enriched, resulting in significant thermal anomalies. Therefore, the exploration of uranium deposits can be achieved to a certain extent by means of thermal infrared (8–12.5 μm) imaging maps.

In oil and gas exploration, hydrocarbons in oil and gas fields migrate vertically upward along pores and micro-fractures, and interact with surrounding materials in form of trace hydrocarbon, forming approximately circular hydrocarbon alteration zones on the surface and near the surface, and generating a series of marks. Thermal anomaly markers can be extracted from thermal infrared (8–14 μm) remote sensing data. This is due to the change of physical and chemical properties of surface materials

after hydrocarbon seepage to the surface or near-surface. Generally, the temperature is 1–3 °C higher than that of surrounding areas. The oil and gas exploration prospects can be planned according to the spectral characteristics of this image.

4.2.1.2 Demand of Infrared Remote Sensing for Disaster Prevention and Mitigation

In the aspect of forest fire monitoring, the fire temperature is generally between 300 and 800 °C when fires occur in forests, grasslands, or bushes. The fire can be well detected and interpreted by infrared remote sensing. With the high resolution and high-sensitivity infrared investigation method, the fire with the low temperature in small area can also be discovered in the early stage.

In the monitoring of spontaneous combustion of underground coal seam, taking Gulaben mining area in Inner Mongolia Autonomous Region, China as an example, in which the small coal fire point is less than 5 m, while the large coal fire area is 30 m. By the spatial infrared thermal imager with the high radiation resolution (0.1 K), the corresponding fire points were accurately captured, thereby the temperature distribution and temperature increase rate in the fire area were judged, so that the over-fire area and fire development trend were accurately obtained to provide accurate data information for timely and accurate effective rescue activities for fire areas, such as coal fields and many small thermal power plants.

In volcanic monitoring, experimental studies have confirmed that there will be obvious abrupt geothermal anomalies in the volcanic area during the precursory period of volcanic eruption, that are related to the diversified factors such as geological structure, volcanic origin, scale, and type. So the abrupt geothermal anomalies in volcanic area are an important sign of thermal infrared remote sensing monitoring and volcanic activity prediction.

4.2.1.3 Requirements on Environmental Protection for Infrared Remote Sensing

With the advancement of industrialization and urbanization, the environmental pollution in China is becoming more and more critical. Although the environmental treatment has made some progress, the overall situation is still grim. Environmental law enforcement urgently needs the daily monitoring of environmental pollution. Space-based high-resolution infrared multispectral remote sensing system has obvious advantages in water pollution, marine oil spill monitoring, and air pollution.

For water environment and pollution monitoring, high-resolution infrared remote sensing satellites can be applied to remote sensing monitoring of key water pollution sources, such as water blooms, red tides, oil spills, and drinking water sources. It mainly includes high-precision monitoring requirements for water body thermal pollution, factory and enterprise sewage (especially at night), estuary water quality

(chlorophyll, water body transparency, and the suspended solids concentration), drinking water source safety, nuclear power plant temperature, and drainage.

For identification and monitoring of oil spill at sea, thermal infrared spectrum (8–14 μm) can be used to identify the occurrence of oil spills, especially at night, to full-time monitor of marine oil spill with high target recognition rate based on different specific heat capacities of seawater and oil.

For atmospheric pollution sources monitoring, high-resolution infrared remote sensing system can effectively monitor the optical thickness of atmospheric aerosol, especially for the fire point of the straw burning in the summer and autumn, dust distribution, illegal emissions from coal-fired power plant in key areas and chimneys of large sewage enterprises such as coal chemical and petrochemical industry. Particularly, it can effectively monitor nighttime emissions.

4.2.1.4 National Security Requirements for Infrared Remote Sensing

With infrared detection method, the working state of the target can be judged by acquiring the temperature information of the target, which is unavailable by visible light and SAR. In the demand of infrared remote sensing for anti-terrorism stabilization, using the temperature-sensitive characteristics of infrared remote sensing method, the terrorist hiding places in no man's land and border areas can be found by the detection of campfires, campsites, and other human activities through its wide-area search and detection capabilities.

In military applications, by obtaining multispectral image information of the same area, not only the satellite image of the target geometry and multispectral fusion from the visible image are obtained, but also the temperature distribution information of the target from the infrared image. Besides, infrared remote sensing can be used to detect various heat source targets, and provide a "suspicious" heat source area for visible light detection and subsequent feature level fusion, thus offering key indicative data for camouflage recognition.

4.2.2 Mission Characteristics

Based on the application requirements of infrared remote sensing satellites in the combination with infrared remote sensing methods, it can be concluded that the mission characteristics of infrared remote sensing satellites are as follows.

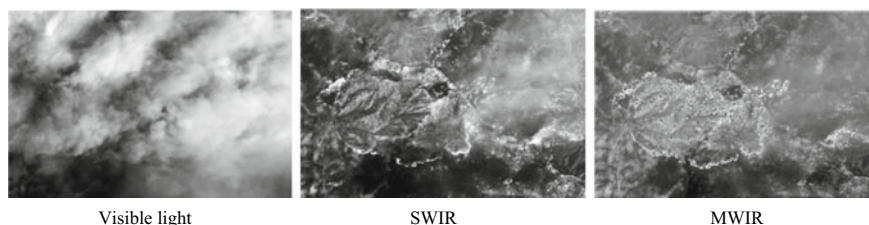


Fig. 4.1 Application of visible light and infrared spectral to the observation of fire points and areas

4.2.2.1 The Efficiency of Optical Remote Sensing Can be Greatly Improved with All-Time Observation

Infrared remote sensing system with the ability to observe all-day time detects the self-heating radiation energy of the object. It can be used for imaging on the Sun-synchronous orbit, the ascending orbit, and the descending orbit. The number of revisits for a specific target is doubled compared to a single visible satellite, thus effectively improving the efficiency of observation. Compared with the visible light band, the infrared band has a longer wavelength and a stronger penetrating ability. For the harsh weather conditions, such as the smoke-filled battlefield environment, the smog-filled fire disaster area and the haze, the infrared band, especially the long-wave infrared band, has significant advantages. Figure 4.1 shows the application effect of visible and infrared bands on the observation of fire points and areas.

4.2.2.2 Using the Unique Infrared Temperature Resolution Capability to Play an Important Role in Various Fields

The target information obtained by infrared remote sensing system is mainly the temperature information of the target. The objects with different temperatures show different gray levels in the image. The temperature resolution capability of the target is utilized regardless of function of resource exploration, disaster prevention and mitigation, pollution detection, work status judgment, and capability for camouflage exposure.

4.2.2.3 The Application Performance Can be Greatly Improved by Infrared Remote Sensing in Combination with High-Resolution Visible Light Imaging or Image Fusion

Due to the particularity of infrared imaging and the limitation of infrared detector manufacturing technology, compared with visible light image, infrared image presents the defects of blurred edge, unclear image, and poor contrast; while visible light image provides more scene details, which reflects the reflection characteristics

of ground objects in visible light spectral. Visible light image conforms to human visual characteristics and is easy to be accepted. In addition, the infrared image is only sensitive to the infrared radiation of the scene, but not to the brightness change of the scene; in contrast, the visible light imaging sensor is only sensitive to the brightness change of the scene, and has nothing to do with the thermal contrast of the scene.

In summary, by virtue of infrared images and visible light images each have their own advantages and disadvantages, infrared image information and visible light image information can complement each other, providing more and more effective information for infrared images and visible light images of the same scene. The fused image retains important details with high local contrast characterization, which helps to improve the application performance of the image.

4.2.2.4 Different Infrared Bands, Different Application Effects

According to the characteristics of infrared wavelength and atmospheric attenuation, infrared atmospheric attenuation in the wavelength range of 3–5 μm and 8–12 μm is relatively low, so the general infrared imaging system works in these two bands.

In the infrared spectrum, the images in medium wave (3–5 μm) and long wave (8–12 μm) can reflect the thermal radiation of the target, with the ability of all-day remote sensing but the different observation characteristics. Table 4.1 gives a comparison of the observed characteristics of the two spectral bands.

As shown in Table 4.1, the combination of the two methods can reveal more information about target thermal radiation. Based on the monitoring requirements, there are not only normal temperature objects, but also a large number of heating targets. Generally, for high-temperature objects, the radiation peak is in the mid-wave region; for normal temperature objects, the radiation peak moves to the long-wave region. In order to detect all kinds of targets effectively, both mid-wave and long-wave infrared bands should be used.

Table 4.1 Comparisons of observational characteristics between medium-wave and long-wave infrared spectral bands

Waveband (μm)	3–5	8–10
Change of radiance with temperature (%/K)	1.7	0.8
Energy distribution	State peak under target thermal start	Peak value at normal temperature
Atmospheric permeability	Weak	Strong
The ability to penetrate thin clouds and mists	Weak	Strong
Solar reflection effect	Strong	Weak
Subjective interpretation	High noise	Low noise

For terrestrial targets with ambient temperature, long-wave band is more widely used in the field of high-resolution remote sensing than mid-wave band because of its high-temperature resolution and less interference of sunlight reflection in images.

4.2.3 Technical Characteristics

Based on the technology development status of infrared remote sensing satellite, the main characteristics of high-resolution infrared remote sensing satellite can be summarized as follows.

4.2.3.1 Compared with Visible Light, Infrared Remote Sensing System is More Difficult to Achieve High Spatial Resolution

Under the same optical system aperture, the geometric resolution of the infrared remote sensing is lower than that of visible light (usually 10–15 times of visible light) because the wavelength is longer than visible light and the diffraction effect is obvious. Therefore, the application efficiency can be greatly improved by on-orbit infrared imaging system combined with high-resolution visible light system.

4.2.3.2 Long Array Infrared Detectors are Difficult to Develop

The device for infrared detector is complex and difficult to production, and should encapsulate the devices in low-temperature Dewar flask for ensuring the performance. So it is difficult for infrared detectors to reach the dimensions of visible light. At present, the infrared array devices can reach 5000–8000 pixels, while the visible light array devices can achieve more than 10,000 pixels by a single chip, and can be also stitched with more than a dozen or even dozens of pieces.

4.2.3.3 High-Sensitivity Infrared Remote Sensing Requires Cryogenic Refrigeration

In order to achieve high sensitivity, the main technical approach of infrared remote sensing is cryogenic refrigeration. At present, the space-based infrared detectors with high sensitivity use refrigerators to cool the detectors to 80 K or even lower, suppressing the thermal noise of the detectors and ensuring imaging performance. With the increasing requirement of infrared sensitivity, cold optics technology is also needed for the follow-up remote sensing satellites to keep the main opto-mechanical component of the camera below 200 K.

4.3 Key Performance Index and Connotation of Infrared Remote Sensing System Imaging Quality

Satellite imaging quality is divided into two parts, i.e., image radiation quality and image geometry quality, which are objectively evaluated by corresponding technical indicators. The integrity of the relevant indicators for evaluating the imaging quality of the satellite should be guaranteed first for the imaging quality of the whole satellite. In addition, satellite imaging links are long, and the factors affecting the imaging quality are various and complex. The correlation between the indicators and the imaging quality should be analyzed comprehensively and objectively.

4.3.1 *Radiation Imaging Quality of Infrared Remote Sensing System*

Radiation imaging quality refers to the ability of remote sensing images to reflect the radiation energy distribution of the observed target, which is affected by many factors and links. The on-orbit dynamic Modulation Transfer Function (MTF), temperature resolution, and dynamic range are the main indicators for evaluating the radiation quality of satellite images, which can not only be quantitatively reflected the impact of each part in imaging process on image, but also guide the engineering design and manufacture of satellite and remote sensing cameras.

- (1) **On-orbit dynamic MTF** of infrared remote sensing satellite is a function of the ratio of image modulation degree to target modulation degree, which represents the transmission capability of satellite for target contrast under different spatial frequencies, and mainly affects the sharpness of remote sensing images. The main factors affecting on-orbit dynamic MTF include atmospheric conditions, camera static MTF, satellite on-orbit push-broom/whisk broom motion, on-orbit space environment, and satellite platform influence.
- (2) **Temperature resolution** of infrared remote sensing satellite is an important performance index of infrared remote sensing, which characterizes the temperature resolution of infrared remote sensing satellite. It is mainly determined by the Noise Equivalent Temperature Difference (NETD) of camera and atmospheric transmittance.
- (3) **Dynamic range** of infrared remote sensing satellite refers to the range between the maximum and minimum input signal that infrared remote sensing satellite can effectively respond to, which characterizes the target equivalent black-body temperature range that the infrared satellite can quantitatively invert. The main influencing factors include external imaging conditions, detector response characteristics, imaging circuit parameters, etc.

4.3.2 Geometric Imaging Quality of Infrared Remote Sensing System

Geometric imaging quality refers to the ability of remote sensing images to correctly describe the geometric shape and position accuracy of objects. The evaluation index of image geometric quality mainly includes geometric positioning accuracy and image distortion, between which geometric positioning accuracy is the main content to evaluate the geometric quality of satellite image. To this end, it is necessary to identify the key influencing factors in the design concept and parameters of satellite, and take targeted measures.

- (1) **Spatial resolution** of infrared remote sensing satellite determines the minimum resolution of the imagery, which is mainly determined by the focal length of the camera, the orbit altitude, and the sampling interval of the detector.
- (2) **Imaging swath** of the infrared remote sensing satellite determines the coverage of satellite image. For the infrared remote sensing satellite with whisk broom mode, the swath depends on the orbit altitude of the satellite and the sweep area of the pendulum mirror; for the infrared remote sensing satellite with push-broom mode, the swath depends on the orbit altitude of the satellite and the focus length of the camera as well as device length.
- (3) **Geometric positioning accuracy** refers to the position accuracy of the camera's optical system pointing to the ground target at a certain moment by means of orbit and attitude determination on the satellite. The main factors affecting the accuracy of geometric positioning include the camera's interior orientation element error, exterior orientation element error, and image distortion. For the infrared remote sensing satellite with push-broom mode, the causes and influencing factors of image distortion are the same as those of the visible light sensing satellite with push-broom mode. For the infrared remote sensing satellite with whisk broom mode, the image distortion includes not only the distortion caused by camera optical system, but also the image distortion caused by whisk broom system. Besides, the main influence factors of scanning distortion also include scanning frequency, scanning surface nonlinearity, image overlap rate, etc.

4.4 Design and Analysis of Imaging Quality of High-Resolution Infrared Camera

4.4.1 Analysis of Key Design Elements for Imaging Quality of High-Resolution Infrared Camera

The imaging quality of infrared camera directly affects the quality of remote sensing image data. The key design elements include the selection of imaging system, the allocation of spectral bands and the determination of spectral band range, the resolution design of ground pixels, the design of imaging swath, the selection of detector and

its focal plane refrigeration module, scanning characteristics (whisk broom system), camera optics system design, stray light suppression design, NETD design, dynamic range design, on-board calibration accuracy design, etc.

4.4.2 Selection of Imaging System

At present, there are two main infrared imaging systems: whisk broom and push-broom.

4.4.2.1 Whisk Broom System

The working principle of the whisk broom infrared camera is to scan along the direction perpendicular to the satellite flight by the pendulum mirror for achieving a larger imaging swath. The advantages of whisk broom infrared camera are that it can use smaller infrared detectors to achieve a larger visual range. Its disadvantage is that due to the size, weight, and disturbance characteristics of the pendulum mirror, the camera aperture should not be too large, and the resolution is difficult to be further improved.

The basic reason for the development of the whisk broom type infrared camera was that the coverage swath of the camera with the push-broom system is only several kilometers under the limitation of the small array size of the infrared detector (hundreds of pixels), which cannot meet the application requirements. With the improvement of the processing level of infrared devices, the size of infrared detector array is becoming larger and larger. In the field of high-resolution Earth observation, the whisk broom system is gradually replaced by the push-broom system.

4.4.2.2 Push-Broom System

With the improvement of the manufacturing level of infrared detectors, the length and scale of linear array of infrared devices gradually increase. The camera can achieve the same coverage swath as the visible light camera without the whisk broom mechanism, thus forming a push-broom type infrared camera. The push-broom type infrared camera system is the same as the visible light imaging system. Its advantage is that it can achieve large aperture and high resolution. Without the moving part of pendulum mirror, i.e., high on-satellite attitude stability, the image quality will not be degraded with the decrease of the satellite body attitude stability.

4.4.3 *Spectral Band Configuration and Spectral Band Range Determination*

Based on the characteristics of infrared wavelength and atmospheric attenuation, the atmospheric attenuation of infrared rays is relatively low in the wavelength range of 3–5 μm or 8–12 μm , so the general infrared imaging system operates in these two bands. Generally, for high-temperature objects, the radiation peak is in the medium-wave region; for normal temperature objects, the radiation peak moves into the long-wave region. In order to detect all kinds of targets effectively, both mid-wave and long-wave infrared bands are used. For terrestrial targets with ambient temperature, the long-wave band is more widely used in the field of high-resolution remote sensing than the medium-wave band because of its high-temperature resolution and less interference from sunlight reflection in images.

The band selection of infrared cameras is also limited by the level of infrared detector and its response characteristics. Due to the limitation of detector performance, the spectral coverage of a certain type of infrared focal plane detector (the corresponding spectral range of 50% peak value) is less than 12 μm , which can only reach about 10 μm . Therefore, the working band of typical satellite infrared camera can be determined as $7.7 \mu\text{m} \pm 0.3 \mu\text{m}$ to $10.3 \mu\text{m} \pm 0.4 \mu\text{m}$.

4.4.4 *Ground Pixel Resolution*

The main factors affecting the ground sampling distance (ground pixel resolution) of the sub-satellite point include the focal length of the optical system, the sampling distance, and the orbit altitude of the detector. When the orbit altitude is fixed, the main factors affecting the ground sampling distance of the sub-satellite point are the focal length of the optical system and the sampling distance of the detector. The formula for calculating the ground sampling distance of the sub-satellite point is as follows:

$$\text{GSD} = d_s \times H/f, \quad (4.1)$$

where GSD is the ground sampling distance of the sub-satellite point, d_s is the sampling interval of the detector, H is the orbital height, and f is the focal length.

4.4.5 *Imaging Swath Design*

For a push-broom type infrared camera, its imaging swath depends on the field of view angle and orbit altitude of the camera optical design. The imaging swath of the sub-satellite point can be approximated as

$$W = 2 \cdot H \cdot \tan(\theta/2), \quad (4.2)$$

where W is the imaging swath; H is the orbit altitude; and θ is the field of view angle of the optical system. However, infrared detectors cannot be stitched like visible detectors under the constraints of refrigerators, so their imaging swath mainly depends on the number of the detector array pixels, that is, the number of pixels multiplied by the ground pixel resolution.

For a whisk broom type infrared camera, its imaging swath mainly depends on its effective scanning field angle and orbit altitude, and its imaging swath of the sub-satellite point can be approximated as

$$W = 2 \cdot H \cdot \tan(\alpha/2), \quad (4.3)$$

where α is the scanning field angle.

4.4.6 Selection of Detector and Its Refrigeration Module for Focal Plane

Infrared focal plane detector is the core component of infrared camera, and its performance directly affects the imaging quality and the reliability of infrared cameras. At present, the detector and its focal plane refrigerator usually adopt the integrated design for ensuring its performance and reliability. By optimizing the operating temperature, refrigeration time, reheat rate, number of switches, and service life of components, a series of consequences such as the high rate of blind pixel and performance degradation caused by the mismatch of their structure and thermal deformation can be avoided. Table 4.2 shows several typical detector refrigeration units, and Fig. 4.2 shows their schematic diagram.

4.4.7 Scanning Characteristic Analysis Based on Whisk Broom Type Imaging System

For a whisk broom type infrared camera, the compliance of the coverage swath, the exactly matched image stitching, and the high quality of geometric imaging of the camera can be ensured by the design and test of scanning characteristics. The following takes a resource satellite with the whisk broom infrared camera as an example to analyze its scanning characteristics.

Table 4.2 Detector refrigerator component

Parameter	Refrigeration module		
	Sofradir Corporation of France		Made in China
	Refrigerator component of 480 × 6 long-wave infrared detector		Refrigerator component of 1024 × 6 long-wave infrared detector
Detector Array/Pixel	480		1024
TDI series	6		6
Range of spectral response/ μm	8–10		8–10
Pixel size/ μm	25.4 (direction of linear array) × 16.6 (direction of TDI)		24 (direction of linear array) × 20 (direction of TDI)
Average peak value D^*	$2.41 \times 10^{11} \text{ cm Hz}^{1/2}/\text{W}$ (300 K blackbody)		$2.3 \times 10^{11} \text{ cm Hz}^{1/2}/\text{W}$
Response rate nonuniformity (%)	4.72		≤ 7
Refrigeration type	Stirling refrigeration		Stirling refrigeration
Operating temperature/K	80 ± 0.5		80 ± 0.5
Lifetime/h	8000		30,000

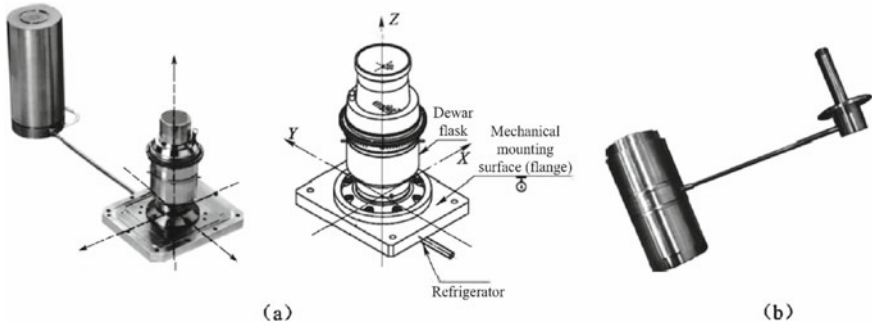


Fig. 4.2 Long-wave infrared detector refrigerator component. **a** Sofradir corporation of France (480×6); **b** Made in China (1024×6)

4.4.7.1 Scanning Period Analysis of Infrared Camera

Infrared camera adopting whisk broom type imaging program, samples at uniform scanning angular velocity, which is not affected by satellite side swing and orbit altitude change. In order to let the infrared camera adapt to the satellite side swing and orbit altitude changes, the scanning frequency shall be determined according to the minimum orbit altitude of the satellite and the imaging state of the sub-satellite point to meet the conditions of neither overlapping nor missing scanning of adjacent scanning swath images. Therefore, after the orbit altitude of the satellite is increased, although the adjacent scanning swath images are overlapped, the overlapping portions can be processed without losing information.

Considering the design margin, a 500 km LEO remote sensing satellite is designed under the conditions that no overlap or leakage occurs in the adjacent scanning swaths when imaging at the sub-satellite point with the orbital altitude of 460 km. Thus, the velocity-height ratio at the equator is 0.015647785, the scanning frequency is 1.576 1 Hz, and the scanning period is 6.345 ms. The sampling period of imaging along the scanning direction is 23.5 μ s.

4.4.7.2 Scanning Parameter Determination

Taking a resource satellite with an optical-mechanical scanning infrared camera as an example, the scanning frequency, effective scanning angle, scanning efficiency, and scanning nonlinearity are the main scanning parameters.

- (1) **Scanning frequency determination.** It must be ensured that there is no leakage (gap) between the adjacent scanning swaths when the satellite orbit altitude is lower than the nominal orbit altitude (480 km). According to the mission requirements, when the satellite orbital altitude is 460 km and the velocity-height ratio at the equator is 0.0156, there is no leakage (gap) in the adjacent scanning swaths, thus the scanning frequency is calculated to be 1.577 2 Hz.

- (2) **Effective scanning angle determination.** According to the requirement of swath width, the effective scanning field of view angle and the corresponding effective scanning angle are calculated to be $\pm 2.0875^\circ$.
- (3) **Scanning efficiency determination.** The higher scanning efficiency can improve the radiation resolution, but the difficulty of scanning control and scanning disturbance will increase. The scanning efficiency is determined to be 40% according to the application requirements and overall design analysis of a resource satellite.
- (4) **Scanning nonlinearity determination.** For the infrared focal plane detector with delay integral system, the scanning nonlinearity should be less than 0.5% to minimize the influence of scanning nonlinearity on TDI imaging.

4.4.7.3 Image Overlap Rate Analysis

The overlap rate of adjacent scanning swaths and the number of overlapping pixels in nominal orbit and high response orbit are calculated based on the scanning frequency of infrared camera. According to the analysis, the overlap rate of adjacent scanning swaths is 4.6%, i.e., about 22 pixels, when infrared camera operates in 480 km nominal orbit.

4.4.8 Design of Camera Optical System

In addition to a relay optical system after the main optical system, the optical system of infrared camera is the same as that of visible light camera. The main function of the relay optical system is to coordinate with the main optical system to achieve joint aberration elimination, so that the light is focused on the photosensitive surface of the detector assembly for secondary imaging. A certain type optical system with whisk

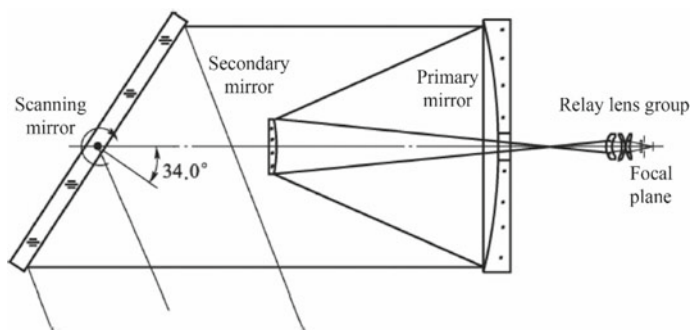


Fig. 4.3 Optical path map of optical system of infrared camera

broom type infrared camera is shown in Fig. 4.3. The design principle of infrared optical system is the same as that of visible light. For details, see Sect. 3.4.8.

4.4.9 Stray Light Suppression

Stray light suppression design is an effective method to ensure the imaging quality of infrared camera, which is of great significance for improving the contrast of imaging, obtaining clear images, and fully utilizing camera performance. Compared with visible light cameras, infrared cameras should consider not only the stray light outside the field of view, but also the spontaneous infrared radiation of the optical elements and the main structure of the camera.

Usually, after the design of stray light elimination, the effect of incident stray light for different angles is analyzed by professional software (such as Tracepro) to determine the effect of stray light suppression. The relationship between stray light coefficient V and MTF is as follows:

$$\text{MTF}_{\text{stray light}} = \frac{M_{\text{target surface stray light}}}{M_{\text{target surface}}} = \frac{1}{1 + V}. \quad (4.4)$$

4.4.10 Noise Equivalent Temperature Difference

The main factors affecting Noise Equivalent Temperature Difference (NETD) of infrared camera include aperture, focal length and optical transmittance of optical system, scanning efficiency (affecting integration time), detectivity of detector, number of parallel-scanning detection elements, and noise of video processing circuit.

NETD is calculated using the following equation:

$$\text{NETD} = 4F^2 / [\delta(2A_d\tau_d)1/2\tau_a\tau_0 D_{\lambda p}^* (\Delta M/\Delta T)], \quad (4.5)$$

where δ is the process factor; F is the F—number of optical system; A_d is the area of sensitive element of detector; τ_d is the integration time of detector; τ_a is the atmospheric transmittance, and $\tau_a = 1$ since the distance of laboratory test is very close; τ_0 is the transmittance of optical system; $D_{\lambda p}^*$ is the peak detectivity of detector; $\Delta M/\Delta T$ is the integral spectral radiosity of the differential spectral radiance emittance in the range of $\lambda_1 - \lambda_2$, which is determined by formula (4.6):

$$\Delta M/\Delta T = \int_{\lambda_1}^{\lambda_2} \frac{\partial M_{\lambda}(T_B)}{\partial T} d\lambda, \quad (4.6)$$

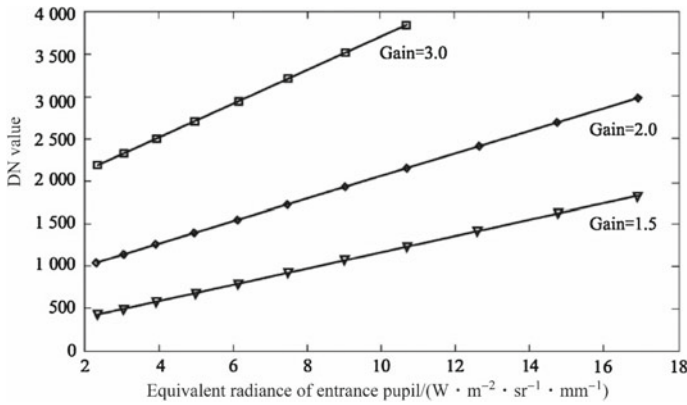


Fig. 4.4 Laboratory calibration curve for a certain type of infrared camera

where $M_{\lambda}(T_B)$ is the spectral radiant emittance and is a function of the blackbody temperature T_B .

4.4.11 Dynamic Range

The dynamic range of the dynamic infrared remote sensing satellite refers to the maximum and minimum input signal range that the infrared remote sensing satellite can effectively respond to, which characterizes the target equivalent blackbody temperature range that the infrared satellite can quantitatively inverse. The main influencing factors include external imaging conditions, detector response characteristics, imaging circuit parameters, etc. which can be obtained from vacuum radiometric calibration test on the ground. The calibration equation corresponding to the probe element can be obtained from the relevant data of vacuum radiometric calibration, and the calibration curve can be fitted by the equivalent radiance of entrance pupil of external calibration blackbody. Figure 4.4 depicts the laboratory calibration curve of an infrared camera. The dynamic range of infrared camera can be obtained by calculating the detectable range of equivalent spectral radiance and corresponding temperature.

4.4.12 Design of On-Satellite Calibration Accuracy

The on-satellite calibration mechanism is usually provided for the accuracy of temperature inversion of infrared camera on orbit. Before each imaging, the high-temperature and low-temperature blackbodies are switched into the back-end optical

path sequentially, and the image of the blackbody is transmitted to the ground for nonuniform correction and quantitative inversion of the ground.

The main factors affecting the calibration accuracy of infrared camera on-satellite radiometric calibration include the vacuum radiometric calibration accuracy before launch and the stability of the calibration device on-satellite after the infrared camera is on orbit. Based on the laboratory test of an infrared camera of a certain resource satellite, the factors influencing the calibration accuracy of the infrared camera on satellite and the analysis method are introduced. From the perspective of vacuum radiometric calibration energy transmission, the factors affecting the accuracy of vacuum radiometric calibration mainly include the following aspects.

4.4.12.1 Black Body Radiator

Blackbody radiation source is the reference source for vacuum radiometric calibration of infrared remote sensor. Generally, the temperature stability of external calibration blackbody, the uniformity of outlet temperature, the precision of temperature control, the temperature uncertainty, and the normal emissivity can reach ± 0.05 K/30 min, ± 0.2 K, ± 0.01 K, ± 0.01 K, and 0.995, respectively. Thermal uncertainty and emissivity error will affect the accuracy of vacuum radiometric calibration. After calculation, the influence of temperature uncertainty and the error of emissivity is 1.78, 0.4%, respectively.

4.4.12.2 Cryogenic Collimator

The collimator used for vacuum radiometric calibration of infrared remote sensor works at low temperature of below 150 K. The infrared remote sensor is calibrated by a collimated extended source. The radiation power received by the infrared remote sensor is affected by the radiation of the optical mirror of the cryogenic collimator itself. For example, assumed that the specular reflection is 0.94, in the range of 7.7–10.3 μm and near 300 K of external blackbody temperature, the mirror temperature is about 150 K, and the influence of radiation itself on the calibration accuracy is 0.03%, then the optical efficiency error of the low-temperature collimator has an effect on the calibration accuracy of 0.85%.

4.4.12.3 Infrared Camera

The output signal instability of infrared remote sensor will affect the calibration accuracy of vacuum radiation. According to the variable temperature data of the main body, the output DN value at 300 K of external calibration blackbody in infrared camera continuously operating is counted. After removing the influence of camera background radiation, the fluctuation of output DN value with time is calculated. The fluctuation of the maximum output DN value of each detector is calculated separately,

and then the arithmetic average value is calculated as the output signal instability of the infrared camera.

In summary, the factors affecting the accuracy of vacuum radiometric calibration mainly include blackbody temperature uncertainty, blackbody emissivity error, collimator optical efficiency error, collimator mirror self-radiation, and the output signal instability of infrared remote sensor.

According to the main factors affecting the accuracy of vacuum radiometric calibration, the total error of vacuum radiometric calibration is about 2%, and the conversion temperature error is ± 1.15 K (300 K blackbody).

The stability of calibration device on-satellite will affect the accuracy of calibration after the infrared camera is on orbit. The blackbody on-satellite for calibration is obtained by blackening on its surface, and the emissivity will not change significantly. The main factors affecting the stability of on-board calibration are the stability of blackbody temperature control and the accuracy of temperature measurement. The calibration blackbody on-satellite has independent primary and backup temperature control and measurement loops, which can be compared with each other. In addition, the ground radiation calibration field can be used to calibrate the infrared camera on orbit, and the calibration device on-satellite can also be calibrated. Considering these factors, the stability of calibration device on-satellite is expected to be less than 1.0 %, which is equivalent to the temperature error of less than 0.6 K at 300 K blackbody. In summary, the calibration accuracy of infrared camera on-satellite can reach 1.3 K (300 K blackbody).

4.5 Program Description of Whisk Broom Infrared Camera System

The working principle of the infrared camera is that the radiation information from the target is transmitted into the main optical device through the lens hood and scanning device, and focuses on the focal plane of the main optical device. Then, the radiation information is relayed to the infrared detector by the relay optical device. The detector adopts a 480×6 linear array infrared focal plane detector with 6-level TDI function, equipping with a Stirling refrigerator.

4.5.1 Definition of Main Functions of Infrared Camera

The main functions of infrared camera are to acquire the geometric features of ground objects and infrared images with high radiation resolution, which include

- (1) According to the task information transmitted from the ground station, the target infrared image data can be acquired by taking photographs over the designated area.

- (2) The on-orbit radiance of entrance pupil of the infrared remote sensing satellite is related to the temperature of the ground object. The infrared radiation intensity of the ground object varies greatly with different types of ground objects in different time periods. In order to obtain high-quality images, the infrared camera should have on-orbit gain adjustment function.
- (3) Infrared camera consists of moving parts such as pendulum mirror and calibration module, which shall be locked in the boost phase of launch and unlocked in on-orbit phase to ensure that the moving parts can adapt to the mechanical environment of the boost phase.
- (4) Image auxiliary data, an important data for ground image processing, shall be organized, arranged on the satellite, and then be downloaded. Therefore, the infrared camera should have the function of receiving auxiliary data sent by satellite-borne computers, and arranging and transmitting them together with the auxiliary data and images of infrared cameras.

4.5.2 Analysis on System Design Constraints

4.5.2.1 Constraints at Task-Level

The Sun-synchronous orbit is usually selected as the satellite orbit under consideration with influence of the solar altitude angle. Based on the demand for solar illumination conditions for spring, summer, autumn, and winter, the influence of solar elevation angle shall be considered for infrared remote sensing satellite systems in principle.

Since the difficulty of high-resolution imaging in the infrared spectrum, it is usually used in conjunction with visible light remote sensing payloads to improve its application performance or compensate for its resolution. Therefore, the satellite orbit is usually selected from the Sun-synchronous orbits with the 10:30 a.m. or 1:30 p.m. local time of descending node and the 450-800 km, orbit altitude. For example, based on the typical application requirements of a resource satellite model in China, the spectral range is from 8 to 10 μm , the ground pixel resolution is from 10 to 20 m, and the imaging swath is over 70 km. To ensure image quality, the on-orbit dynamic MTF should be better than 0.1, and the on-orbit temperature resolution is better than 0.2 K (300 K blackbody).

4.5.2.2 Constraints on Large-Scale Engineering Systems

The detector of the infrared camera works at low temperature, so the refrigerator must be turned on in advance for a period before the infrared camera detects the target object, so as to cool the focal plane of the infrared detector to the operating temperature. In addition, the high-temperature and low-temperature blackbody should be imaged sequentially to obtain the calibration data before the infrared camera imaging

to quantitatively invert the infrared image and correct the nonuniformity. The auxiliary data broadcasted by satellite bus is received by infrared camera and arranged and transmitted together with the auxiliary data and images of infrared cameras to the ground application system.

4.5.2.3 Constraints on Satellite Overall Design

In order to ensure the on-orbit performance, reliability and interface compatibility between subsystems of infrared cameras, constraints on infrared cameras system design are to be put forward. Taking the infrared camera in a certain satellite as an example, it is specified for the static transfer function higher than 0.18, the dynamic range better than 240–340 K, and the NETD better than 0.15 K (300 K blackbody) to ensure the quality of on-orbit dynamic imaging. In order to reduce the distortion of infrared image, the performance of scanning mechanism is constrained, which is specified for the scanning frequency at 1.577 2 Hz, the effective scanning angle within $\pm 2.087^\circ$, the scanning efficiency at 40%, the scanning nonlinearity less than 0.5%, and satellite design life more than five years.

4.5.3 Configuration and Topology of Infrared Camera System

Infrared camera images in the direction of satellite trajectory by satellite flight motion and the scanning mirror's whisk broom motion. One-dimensional linear mechanical whisk broom scanning imaging scheme is adopted, several scanned swaths are put together to form an image. As shown in Fig. 4.5, infrared camera is composed of infrared camera main body, infrared camera manager, and infrared camera refrigeration controller.

The main body of the infrared camera is used for collection of infrared radiation information, focusing, and imaging; photoelectric conversion; signal amplification; analog to digital conversion; and coding output. The infrared camera works with infrared camera manager and infrared camera refrigeration controller to complete the functions of imaging, on-satellite calibration, gain adjustment, focusing, on-orbit locking and unlocking of scanning mirror, focusing device, the calibration device, primary and backup optical path switching, and infrared detector refrigeration.

Infrared camera manager is used for infrared imaging control, telemetry and remote control management, power distribution management, etc. The infrared camera refrigeration controller is used to control the refrigerator, mechanical lock, focusing device, and switching mechanism.

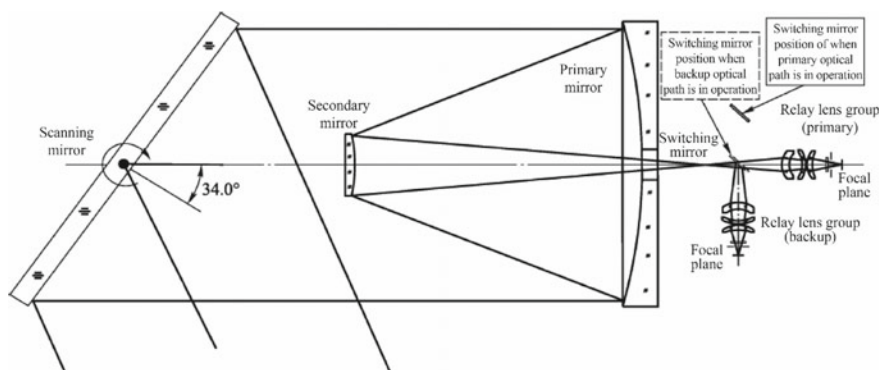


Fig. 4.6 Optical layout of infrared camera

4.5.6 Scanning System Concept

The scanning system consists of a scanner and a scanner controller. The block diagram and interface of the system are shown in Fig. 4.7.

For the scanning mirror, the mass and inertia shall be as small as possible to reduce the influence of the scanning mirror on the service life of the supporting component and the influence of the whisk broom on the attitude of the satellite, so as to better ensure the image quality. The scanning mirror module is composed of a scanning mirror body, a pivot, etc.

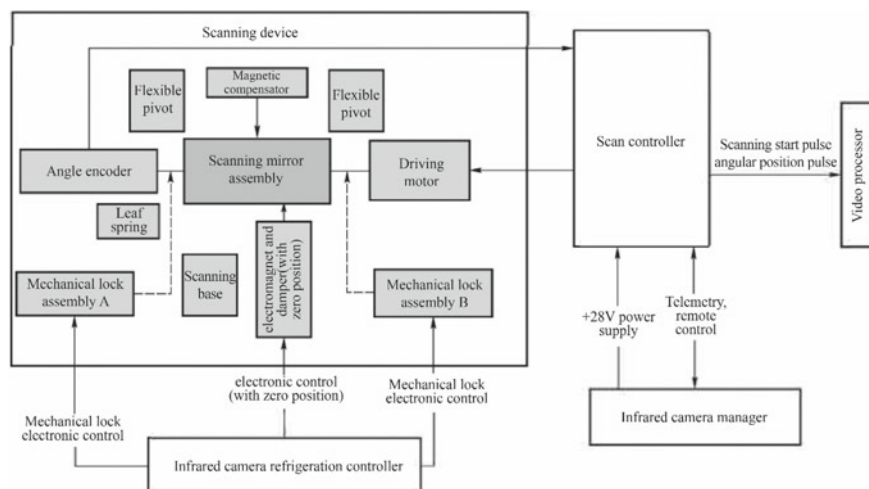


Fig. 4.7 Block diagram of composition of scanning subsystem and interface

Table 4.3 Technical indicators of devices

Items	Technical indicators
Detector array size	480×6
F-number	2.62
Spectral range/ μm	7.7 ± 0.3 to 10.3 ± 0.4
Average peak detection rate/($\text{cm Hz}^{1/2} \bullet \text{W}^{-1}$)	$\geq 2.0 \times 10^{11}$
Refrigerator cooling capacity/mW (@ 80 K, 23 °C)	1000
	60
Cooling time/min	≤ 8

4.5.7 Infrared Detector and Its Refrigerator Component Scheme

Detector refrigeration unit is an imported device. Its core equipment is a 480×6 TDI photovoltaic HgCdTe infrared focal plane detector based on CMOS readout circuit, which is packaged in metal Dewar. The refrigerator is a split linear drive Stirling refrigerator. The core indicators of the detector are shown in Table 4.3.

4.5.8 Electronic System

The electronic subsystem of infrared camera includes remote control and telemetry management, imaging control, primary/secondary power distribution, power supply/drive/bias/video signal processing of imaging circuit, image data encoding, scanning control, refrigerator control, calibration control, high-temperature and low-temperature blackbody temperature control, light path switching control, mechanical lock, and focusing motor control, etc., which can be divided into three single units.

4.5.9 Camera Thermal Control Scheme

The main body temperature control system of infrared camera adopts the scheme of passive temperature control as primary scheme and active temperature control as auxiliary one. The key point is to control the temperature gradient in the camera.

Passive temperature control measures include that the outer surface of the main body of the camera is coated with multilayer insulation material to reduce the heat exchange between the main body and its environment, and the heat generated by the heating device is dissipated by using high-efficiency heat conduction device and radiator plate.

Active temperature control measures include installing several heaters and temperature sensors in the proper position of the camera, forming a temperature control loop with the load thermal control management unit, controlling the temperature of the main body of the camera, so that the camera can work steadily.

4.6 Design and Analysis of On-Orbit Dynamic Imaging Quality of Infrared Remote Sensing Satellite

4.6.1 Analysis of On-Orbit Dynamic Imaging MTF

Infrared remote sensing uses whisk broom imaging system. The influence factors of dynamic MTF on orbit are different from that of visible light push-broom imaging system. There is no difference in MTF in push-broom direction and no correction of deviation angle. The imaging link and influence factors of on-orbit MTF of infrared camera are shown in Fig. 4.8.

If the entire imaging link system is regarded as a linear system of spatial frequencies, the MTFs of each unit are multiplied to determine the overall modulation response of the entire system, that is, the on-orbit MTF can be obtained by Eq. (4.7).

$$\text{MTF}_{\text{on-orbit}} = \prod_{i=1}^n \text{MTF}_i. \quad (4.7)$$

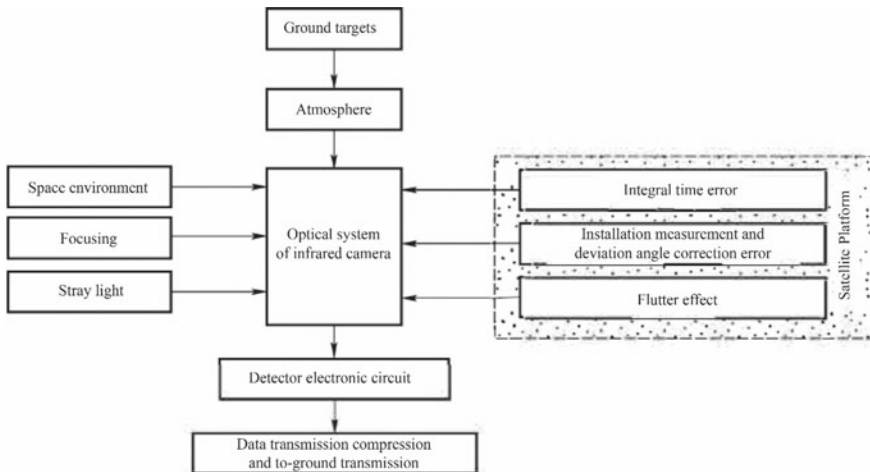


Fig. 4.8 Imaging link of infrared camera

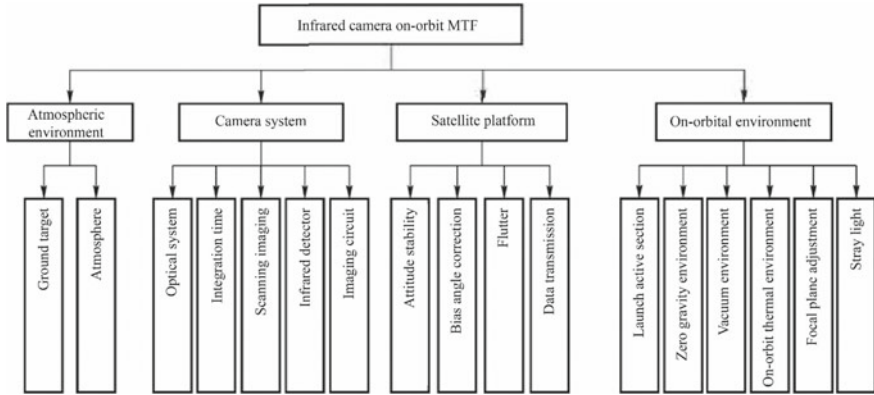


Fig. 4.9 Main factors affecting on-orbit dynamic MTF of infrared camera

Considering that the infrared camera scans the ground objects crossing the direction of the trajectory of the satellite, the system MTF of the scanning direction of the infrared camera can be decomposed as shown in Fig. 4.9.

The satellite on-orbit dynamic MTF can be described as

$$\begin{aligned} \text{MTF}_{\text{total scan}}(\nu) &= \text{MTF}_{\text{atmospheric environment}} \times \text{MTF}_{\text{camara}}(\nu) \\ &\times \text{MTF}_{\text{satelliteplatform}} \times \text{MTF}_{\text{on-orbit environment}}, \end{aligned} \quad (4.8)$$

where $\text{MTF}_{\text{atmospheric environment}} = \text{MTF}_{\text{atmospheric}}$;

$$\begin{aligned} \text{MTF}_{\text{camara}}(\nu) &= \text{MTF}_{\text{optical system}}(\nu) \times \text{MTF}_{\text{detector}} \times \text{MTF}_{\text{integrationtime}} \\ &\times \text{MTF}_{\text{circuit}} \times \text{MTF}_{\text{push broom}}; \end{aligned}$$

$$\begin{aligned} \text{MTF}_{\text{satellite platform}} &= \text{MTF}_{\text{correction of deviation angle}} \times \text{MTF}_{\text{attitude stability}} \times \text{MTF}_{\text{flutter}} \\ &\times \text{MTF}_{\text{data transmission}}; \end{aligned}$$

$$\begin{aligned} \text{MTF}_{\text{on-orbit environment}} &= \text{MTF}_{\text{launch}} \times \text{MTF}_{\text{thermal}} \times \text{MTF}_{\text{force}} \\ &\times \text{MTF}_{\text{vacuum}} \times \text{MTF}_{\text{focusing}} \times \text{MTF}_{\text{straylight}}; \end{aligned}$$

and Y is the sampling frequency.

4.6.1.1 Camera Static MTF Determination

Static MTF of infrared camera is determined by MTF of the optical system, the infrared detector, the video processing circuit, and other links such as focusing. Its value is approximately equal to the product of the MTFs of the above parts.

MTF of optical system is equal to the MTF value of optical system design multiplied by processing and adjusting MTF. For the MTF of the optical system, the average MTF of the infrared camera at Nyquist frequency in the full spectrum and full field of view is designed on the basis of the aperture, focal length, and field of view angle of the optical system. The processing and adjusting MTF of the optical system of satellite infrared camera is determined through the actual results of the multi-camera installation and adjustment.

MTF of detector and circuit. According to relevant test and analysis, MTF of infrared detector can reach 0.57. Based on experience, the MTF of video processing circuit can generally achieve over 0.98.

MTF of focal plane assembly and adjustment link is 0.97 on the basis of past experience.

Considering the above several aspects, the static MTF value is specified for the whole infrared camera as 0.184.

4.6.1.2 Atmospheric Impact Analysis

Infrared cameras image on ground targets by passing through the atmosphere, and the influence of the atmosphere on the thermal radiation information of ground objects will result in a certain degree of image blurring, which is mainly caused by atmospheric turbulence and aerosol scattering and absorption. Compared with the visible light camera, the infrared camera has longer wavelength and lower resolution of ground pixels at the same aperture, whose MTF is less affected by atmospheric turbulence and disturbance than that on visible-band camera. According to the on-orbit test data of satellites, the MTF influence factor of atmosphere on infrared camera is specified at about 0.9.

4.6.1.3 Impact Analysis of Scanning Motion

Whether it is a whisk broom type or push-broom type infrared camera, an inherent descent factor can be used to represent scanning motion:

$$\text{MTF}_{\text{pushbroom}} = \frac{\sin(\pi v_n d)}{\pi v_n d}, \quad (4.9)$$

$$v_n = \frac{1}{2p}, \quad (4.10)$$

where d is the image shift distance (pixel) in an integral time; v_n is the sampling frequency, i.e., Nyquist frequency sampling; and p is the detector pixel size.

For infrared detectors, especially for long-wave infrared devices, the integration time of the devices is usually short, about 20 μs , which is much shorter than the time that a satellite flies over or a pendulum mirror scans over a sampling distance on the

ground. Therefore, the MTF drop caused by whisk broom or push-broom of infrared cameras is usually negligible.

4.6.1.4 Analysis of Attitude Stability Effect

Infrared camera adopts the whisk broom type imaging mode based on TDI infrared focal plane detector. During on-orbit flight, satellite attitude changes will produce image shift on the focal plane, resulting in a decline of MTF, thus affecting the imaging quality.

Because of the slow change of satellite attitude, the integration time of infrared camera detector is very short (single-order integration time is about $20\ \mu\text{s}$), the TDI series is only 6, and the change of satellite attitude can be approximated to linear change. Under the condition of 6-order TDI imaging, the image shift caused by the change of satellite attitude is

$$\Delta d = f \times N_{\text{TDI}} \times \omega \times t, \quad (4.11)$$

where Δd is the image shift caused by satellite attitude change under the condition of 6-order TDI imaging; f is the focal length of the camera; N_{TDI} is the TDI series, its maximum value is 6; ω is the angular rate of satellite attitude change. The simulation and on-orbit verification show that the attitude stability of the infrared camera is higher than $1.0 \times 10^{-3}^\circ/\text{s}$, and t is the time corresponding to the single-order TDI.

It is calculated that the image shift during the integration time is very small relative to the pixel size, and its influence on the MTF can be ignored.

4.6.1.5 Analysis of Correction Effect of Deviation Angle

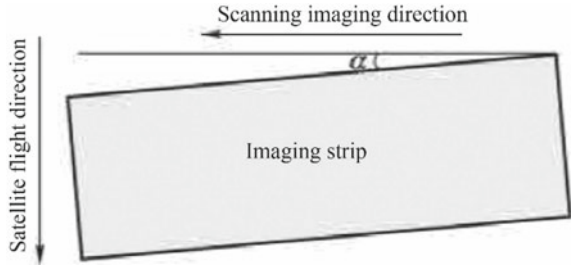
(1) Correction of deviation angle in whisk broom type infrared camera.

For the whisk broom type infrared camera, the projection of the scanning swath to the ground is horizontal and perpendicular to the direction of the detector array. The ground velocity of the ground target relative to the infrared camera is determined by the resultant vectors of the satellite flying speed $V_{\text{satellite flight}}$, the scanning speed $V_{\text{whisk broom}}$ of the scanning mirror on the ground, and the Earth rotation speed.

The scanning swath inclines along the satellite's flight direction under the influence of the satellite's flight motion. The inclination angle is related to the satellite flying speed $V_{\text{satellite flight}}$ and the scanning speed $V_{\text{whisk broom}}$ of the scanning mirror on the ground under comprehensive consideration of the satellite orbit, the camera scanning frequency, and the Earth rotation speed.

The angle between the satellite flight speed $V_{\text{satellite flight}}$ and the scanning mirror scanning speed $V_{\text{whisk broom}}$ can be calculated as $\tan \alpha = V_{\text{satellite flight}}/V_{\text{whisk broom}}$, and the image distortion can be eliminated by mounting the detector array with angle α to the focal plane of the infrared camera, as shown in Fig. 4.10.

Fig. 4.10 Influences of satellite flight on infrared scanning trajectory



The drift correction angle of satellite platform varies in a certain range. The drift correction error is calculated in the range of vector angle between the scanning speed $V_{\text{whisk broom}}$ of infrared camera and the satellite flight speed $V_{\text{satellite flight}}$.

The image shift l caused by drift correction error (pixel number):

$$l = N \cdot \tan \theta. \quad (4.12)$$

According to a comprehensive analysis, the effect of drift correction error on MTF can be neglected.

- (2) Effect of the drift correction angle on installation of whisk broom type infrared camera and push-broom visible camera mounted on same platform.

When the whisk broom type infrared camera and high-resolution visible light camera are mounted on the same platform, the correction of deviation angle should first satisfy the correction requirements of visible light camera because the TDI series and resolution of visible camera are much higher than these of infrared camera. In this circumstance, the scanning swath coverage characteristics of infrared cameras will be affected to some extent, which should be paid attention to in the ground image processing.

The whisk broom type infrared camera stitches several sub-frame strips obtained by multiple single scanning to form an image. Figures 4.11 and 4.12 show the stitching of two scanning strips of the infrared camera, where X_o , Y_o , Z_o , and X , Y , and Z are orbital coordinates and satellite body coordinates, respectively. α is the correction value of satellite drift angle when imaging, which can be obtained from the auxiliary data of the frame image.

It can be concluded that the angle between the sawtooth of two adjacent image strips of the infrared camera imaging in descending orbit segment can be calculated by subtracting the correction value of deviation angle from the installation angle of the detector, while the angle between the imaging strips in ascending orbit segment can be obtained by adding the correction value of deviation angle and the installation angle of the detector.

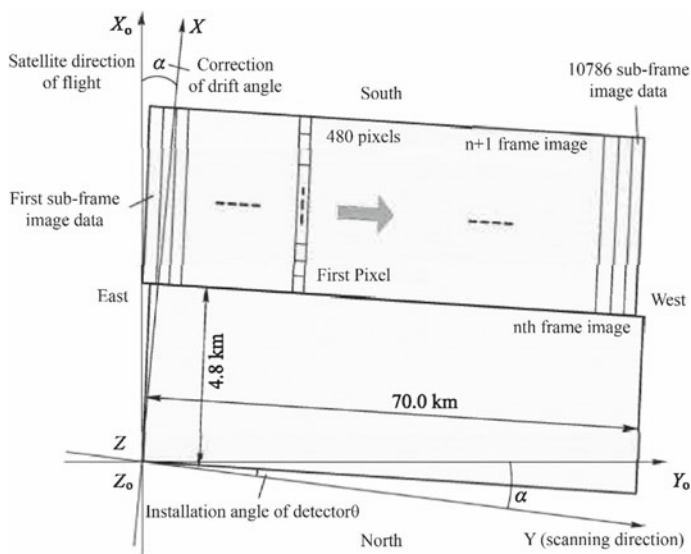


Fig. 4.11 Schematic diagram of ground coverage for infrared camera imaging in descending orbit segment

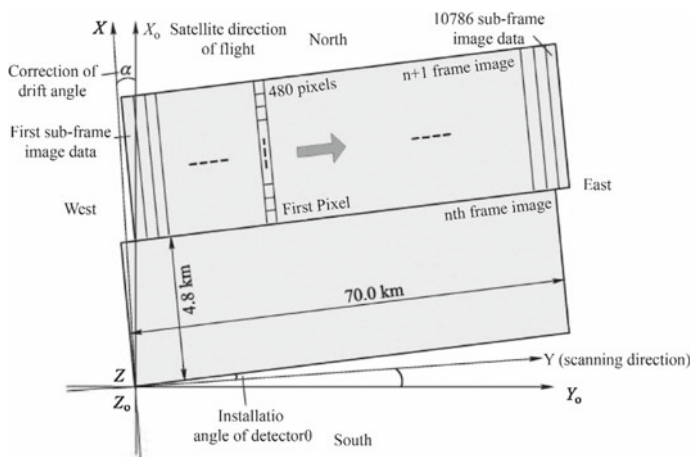


Fig. 4.12 Schematic diagram of ground coverage for infrared camera imaging in ascending orbit segment

4.6.1.6 Analysis of Micro-vibration Effect

During satellite on-orbit imaging, the motion of various moving parts on the satellite, such as solar wing stepping, momentum wheel, control moment gyroscope, will cause small and high-frequency vibration of the satellite body, and cannot be measured

and suppressed by the control system. Therefore, it will have a certain impact on the quality of imaging.

Since the resolution of the infrared camera is much lower than that of the visible light, the disturbance source on satellite has little influence on the infrared camera. Generally, the influence of the disturbance source on MTF of the infrared camera can be neglected. However, the infrared camera itself has many moving parts, such as the pendulum mirror of the whisk broom type system infrared camera and the refrigerator for the infrared detector, whose impact on the imaging quality of the high-resolution visible/infrared integrated remote sensing satellite is not negligible, especially effects on the imaging of visible light cameras mounted on the same platform.

4.6.1.7 Analysis of Stray Light Effect

The ideal light source signal is used in ground MTF test of infrared camera, but the on-orbit imaging will be affected by the light source outside the field of view, which is different from the ground object surface light source. In order to reduce the influence of stray light on image quality, infrared camera must adopt the design of eliminating stray light. According to the system analysis, the stray light coefficient is not more than 3%. The influence factor of stray light on image quality is 0.97.

4.6.1.8 The Effect of Thermal/Mechanical Stability on MTF of Camera On-Orbit

Although the dynamic imaging performance of satellite on-orbit is verified to some extent by the ground tests on the adaptability of the camera to the on-orbit space environment, such as the mechanical environment of the boost phase, the on-orbit thermal environment, and the on-orbit weightlessness environment simulated by the camera flip of 180°. Considering the difference between the ground test and the on-orbit flight environment, it is still possible to cause defocusing, especially for high-resolution cameras, which need to set on-orbit focusing function. The effect of camera defocus on MTF can be determined by Eq. (4.13).

$$\text{MTF}_{\text{defocusing}} = 2J_1(X)/X, \quad (4.13)$$

where J_1 is the first-order Bessel function; $X = \pi d v_n$, d is the diffuse circle diameter caused by defocusing, $d = \Delta / F^\#$, Δ is the defocusing amount, $F^\#$ is the reciprocal of the relative aperture, and v_n is the characteristic frequency, which can be regarded as the spatial frequency corresponding to the Nyquist frequency. When the camera has a focusing accuracy far higher than the focal depth, the $\text{MTF}_{\text{thermal/force}}$ of the focusing link can be defined as 0.98.

4.6.1.9 Assessment of On-Orbit Dynamic Imaging MTF

For the infrared remote sensing satellite system, the dynamic MTF of all links and elements on orbit is also analyzed based on the outcome of satellite system design and product implementation, and the design rationality and effectiveness of the system are analyzed with MTF at Nyquist frequency as the evaluation criterion. For example, for a resource satellite with 480×6 level long-wave infrared TDI detector, the infrared camera with the whisk broom type imaging system is selected according to the typical application, so as to achieve a wide range to solve the problem of detector array constraints. The relationship between the on-orbit dynamic MTF and the MTF influencing factors in each link is as follows:

$$\begin{aligned} \text{MTF}_{\text{system}}(v_n) = & \text{MTF}_{\text{atmosphere}} \times \text{MTF}_{\text{camara}}(v_n) \times \text{MTF}_{\text{attitudestability}} \times \text{MTF}_{\text{drift angle}} \\ & \times \text{MTF}_{\text{flutter}} \times \text{MTF}_{\text{straylight}} \times \text{MTF}_{\text{thermal/force}} \end{aligned} \tag{4.14}$$

The on-orbit dynamic MTF is systematically analyzed based on the analysis results of the foregoing sections in this chapter, and its results are detailed in Table 4.4. It can be concluded that there is no MTF degradation caused by the control accuracy of flight direction and drift angle, the resolution is low and has little effect on flutter for the infrared camera with whisk broom type imaging system.

4.6.2 Analysis of On-Orbit Dynamic Range

The on-orbit dynamic range of satellite infrared camera depends on the dynamic range of the camera. The design and test of the dynamic range of the camera are detailed in Sect. 4.4.11.

Table 4.4 On-orbit dynamic MTF assessment of satellites

Influence factor	MTF
Camera Static MTF	0.184
Atmosphere	0.800
Attitude stability	0.999
Flutter	0.999
Microgravity environment on-orbit	0.999
Drift angle	1.0
Thermal/mechanical environment on-orbit	0.94
Influence of stray light	0.97
Total	0.13

4.6.3 Analysis of On-Orbit Temperature Resolution

Considering that there is no obvious change in the noise characteristics of infrared camera after launching, the on-orbit temperature resolution is mainly determined by NETD and atmospheric transmittance before launching. Assuming that the temperature difference between the target and the background on the ground is ΔT , the apparent temperature difference to the pupil of the infrared camera can be calculated by the following formula:

$$\Delta T_{\text{app}} = \tau_{\text{atm-ave}}^R \Delta T,$$
 (4.15)

where ΔT_{app} is the apparent temperature difference, $\tau_{\text{atm-ave}}^R$ is atmospheric transmittance.

4.6.3.1 Analysis of Atmospheric Transmittance

The atmospheric environment is ever-changing, and its transmittance varies sharply with the atmospheric composition, so it is difficult to give exact data on atmospheric transmittance. The following uses the software Modtran to illustrate the atmospheric effects by taking the typical atmospheric model in different regions as an example.

Modtran modeling parameters: the atmospheric model is set as mid-latitude summer standard atmosphere; the atmospheric attenuation type as mid-latitude summer, winter, etc. the visibility as 5, 23 km, etc.; the atmospheric scattering type as with multi-scattering modes.

The atmospheric transmittance under various conditions is calculated and shown in Table 4.5.

Table 4.5 Atmospheric transmittance and temperature resolution under various conditions

Atmospheric model	Visibility 5 km		Visibility 23 km	
	Atmospheric transmittance	Temperature resolution/K	Atmospheric transmittance	Temperature resolution/K
Mid-latitude summer	0.420	0.126	0.494	0.109
Mid-latitude winter	0.600	0.09	0.646	0.084
Near arctic summer	0.525	0.103	0.560	0.096
Near arctic winter	0.646	0.084	0.700	0.077
American standard atmosphere of 1976	0.560	0.096	0.600	0.09

4.6.3.2 Noise Equivalent Temperature Difference (NETD)

The main factors affecting the NETD of infrared camera are the aperture, focal length, optical transmittance of the optical system, scanning efficiency (affecting integration time), detector detection rate, and number of parallel-scanning detection elements, noise of video processing circuit, etc.

Increasing the aperture of the optical system, improving the performance of the detector, and prolonging the integration time of the detector are the main ways to improve the resolution. The increase of the aperture of the optical system is an effective way to improve the temperature resolution even when the performance, integration time, and swath of the detector are constant, but this will lead to the increase of the volume and weight of the camera.

The calculation method of NETD can be determined by formulas (4.5) and (4.6), with $\lambda_1 = 7.7 \mu\text{m}$, $\lambda_2 = 10.3 \mu\text{m}$, $T_B = 300 \text{ K}$, $\delta = 0.85$, $F = 2.62$, $A_d = 0.0028 \times 0.0038 \text{ cm}^2$, $\tau_d = 21 \mu\text{s}$, $\tau_d = 1$, $\tau_0 = 0.75$, $D_{\lambda_p}^* = 2.45 \times 10^{11}$. By Formula (4.6), $\Delta M / \Delta T = 7.939 \times 10^{-3} \text{ W/cm}^2$, and then $\text{NETD} = 83 \text{ mK}$.

4.6.3.3 On-Orbit Temperature Resolution Assessment

The on-orbit temperature resolution of satellite is predicted as 0.1–0.14 K by calculating or measuring the atmospheric transmittance and NETD.

The temperature resolution under various atmospheric conditions is calculated and shown in Table 4.5.

4.6.4 Analysis of Strip Stitching Characteristics

For the infrared camera, the adjacent scanning swath images shall not overlap and miss scanning by adaption to the change of satellite orbit altitude when imaging at the satellite minimum orbit altitude and sub-satellite point. This ensures that there is some overlap between adjacent scanning strips at higher orbit altitude. The overlap rate varies with the orbit altitude and flight speed, and the overlapped part can be eliminated without loss of information.

When image processing is carried out on the ground, the image overlap of adjacent scanning strips can be calculated according to the satellite height and other parameters corresponding to the imaging position, and the continuous image can be obtained by eliminating the overlap part. Therefore, the whisk broom type imaging mode of infrared camera can adapt to the change of satellite orbit altitude.

The overlap rate and the number of overlap pixels between adjacent scanning strips at different orbital heights are analyzed and calculated. The results are shown in Table 4.6. According to the data in the table, the scanning on normal orbit and the daily recursive orbit will not be missed.

Table 4.6 Scanning strips stitching characteristics of infrared camera

Orbit altitude	Overlap rate/%	Number of overlap pixels
The lowest orbit 460 km	0	0
Nominal orbit 480 km	4.6	22
Daily recursive orbit 568 km	20.83	100

Table 4.7 Analysis of optical distortion of infrared camera

FOV/(°)	Proportional FOV/ ω	Distortion/%
0	0	0
0.12	0.4	−0.16
0.24	0.8	−0.22
0.3	1	0.5

4.6.5 Image Distortion Analysis

In the process of scanning and imaging, the optical system, scanning motion characteristic, and correction of the drift angle of the whole satellite will lead to a distortion of infrared image. The influence of the above-mentioned factors on image distortion can be processed by ground precise measurement data and the number of auxiliary data segments. In this section, the conformity of each influencing factor is analyzed to ensure that the image can be processed effectively on the ground.

4.6.5.1 Analysis of the Influence of Optical System Distortion

Considering that the change of space environment may cause the change of optical lens inclination, the distortion of the optical system of a resource infrared camera is analyzed through the analysis of the optical system. As shown in Table 4.7, it can be used as a reference for the geometric correction of the infrared camera image.

The optical system of infrared camera is relatively small in scale, the camera and optical lens are made of high-rigidity, temperature-insensitive ferroalloy, silicon carbide, and other materials. Combined with the precise temperature control of the whole satellite and camera, the on-orbit distortion of infrared camera is relatively stable and can be calibrated as system error on the ground.

4.6.5.2 Scanning Performance Impact Analysis

The infrared camera adopts the whisk broom type imaging scheme through the direction of satellite flight trajectory, and combines with the direction of satellite flight

to continuously stitch the scanned strips. Therefore, the scanning performance indicator directly affects the imaging quality of infrared camera. The main scanning performance requirements of infrared cameras are shown in Table 4.8.

(1) Scanning frequency

After fine-tuning of the scanner and the control circuit, the scanning frequency is tested. The test curve is shown in Fig. 4.13, and the test result is 1.577 2 Hz.

(2) Scanning nonlinearity

The scanning nonlinearity of the infrared camera prototype scanning device is tested by the linearity tester after the fine-tuning of the control circuit. According to the definition of scanning nonlinearity, it is the maximum deviation of the average angular velocity from the arbitrary angular velocity in the scanning linear segment. Figure 4.14 depicts the test results of effective scanning field of view, the effective angle of the scanning linear segment is better than -2.087 ° to $+2.087\text{ }^{\circ}$.

Table 4.8 Main scanning performance of infrared camera

Items	Parameters	Notes
Scanning frequency/Hz	1.577 2	
Scanning nonlinearity/%	≤ 0.5	Effective scanning of the field of view
Scanning profile nonlinearity/pixels	$\leq 1\uparrow(\text{peak})$	Deviation of scanning profile from ideal transverse linear scanning
Scanning profile repeatability/pixels	$\leq 3\uparrow$	Repeatability of two scanning lines

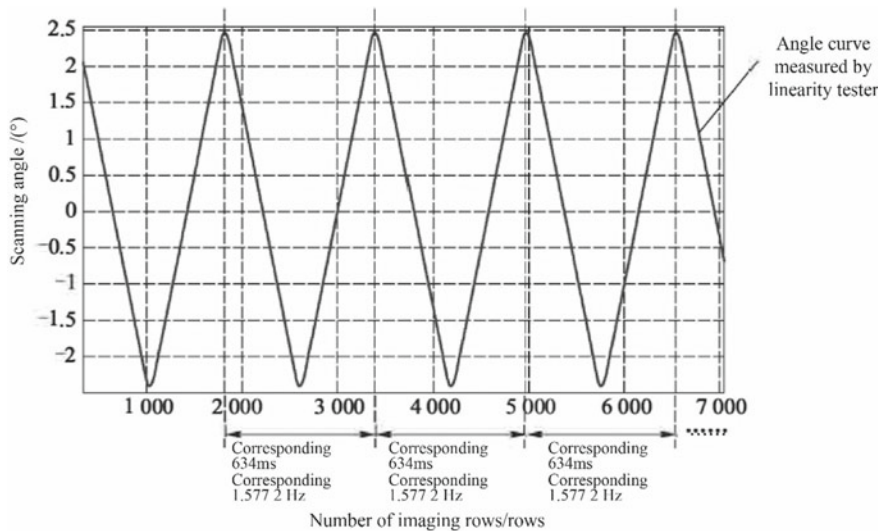


Fig. 4.13 Scanning motion time-angle curve

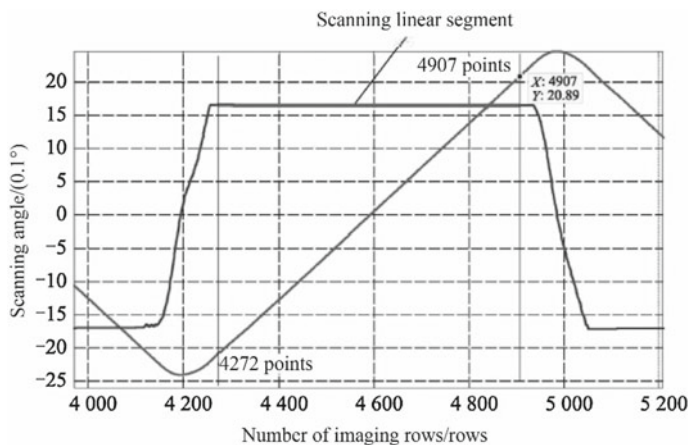


Fig. 4.14 Effective scanning FOV test curve

The measurement results of scanning nonlinearity are shown in Fig. 4.15. It can be seen from the figure that the maximum velocity is $16.55^\circ/\text{s}$, the minimum velocity is $16.46^\circ/\text{s}$, the average velocity of the whole linear segment is $16.49^\circ/\text{s}$, and the computational nonlinearity is 0.4%.

(3) Repeatability of scanning profile

Through continuous sampling of 100 frames of T15 target images, a segment of images is intercepted vertically in each frame, and these intercepted 100 frames are stitched. The repeatability of images is calculated according to the stitched images. Scanning repetitive stitching images are shown in Figs. 4.16 and 4.17, where the maximum deviation is within $\pm 3.6''$, corresponding to 2.5 pixels.

(4) Scanning profile nonlinearity

100 frames of thin rod target images are collected continuously, and a segment is intercepted horizontally from each frame. Those intercepted segments are stitched, and the repeatability of the images is calculated according to the stitched images. The scanning profile nonlinear stitched images and calculation results are shown in Figs. 4.18 and 4.19. As can be seen from the figure, the scanning profile nonlinearity is one pixel.

4.7 Infrared Remote Sensing System Calibration Technology

The calibration of infrared remote sensing system mainly includes laboratory vacuum radiometric calibration and on-orbit calibration.

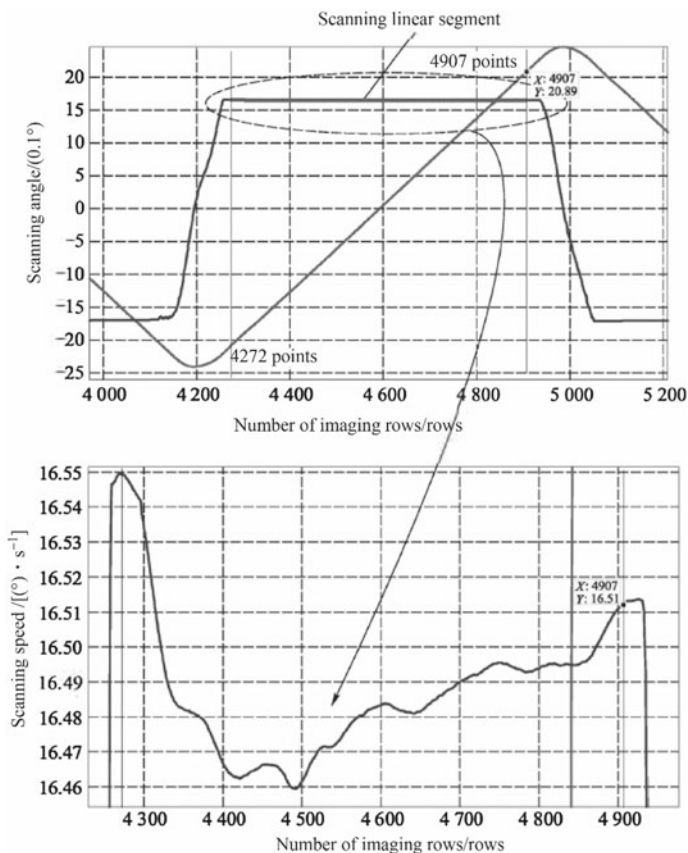


Fig. 4.15 Scanning time-speed curve and partial enlargement of linear segment

4.7.1 Ground Vacuum Radiometric Calibration

Unlike visible light cameras, vacuum radiometric calibration experiments should be carried out in vacuum tanks to accurately calibrate the response characteristics of infrared cameras on the ground, because the optical components and supporting structures of infrared cameras can spontaneously radiate infrared spectra, and the ambient air can also generate spontaneous radiation in infrared band vacuum radiometric calibration.

The purpose of vacuum radiometric calibration is to obtain the calibration equation of each detector element and the correction coefficient related to the calibration, measure the dynamic range of infrared camera, and provide the basis for the quantitative application of infrared camera on-orbit acquisition of image data by measuring the radiation in the simulated space environment of the infrared camera. The test



Fig. 4.16 Scanning profile repeatability (after nonuniform correction)

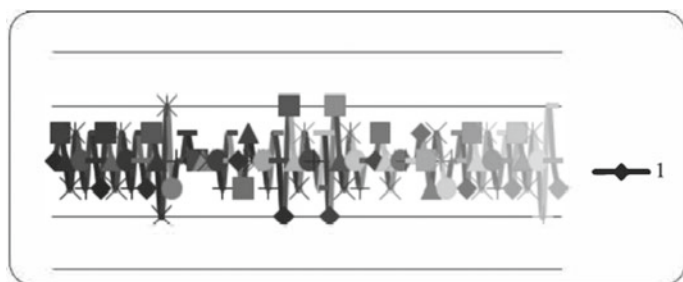


Fig. 4.17 Scanning profile repeatability calculation result

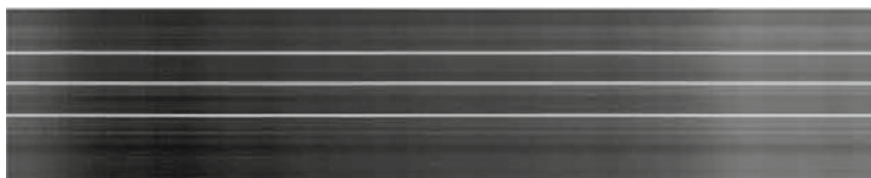


Fig. 4.18 Scanning profile nonlinearity (after nonuniform correction)

equipment includes vacuum tank, standard radiation source, low-temperature collimator, etc. The response characteristic curves of each detector element are obtained by adjusting the blackbody temperature.

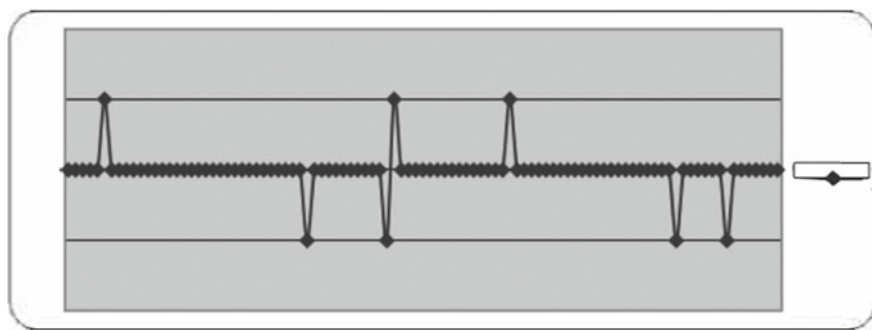


Fig. 4.19 Scanning profile nonlinearity

4.7.2 On-Orbit Calibration

The on-board calibration accuracy of infrared camera depends on the calibration accuracy before launching and the change of infrared camera (including on-board calibration device) after launching and that of on-orbit environment.

The absolute radiometric calibration method before satellite launch is mainly vacuum radiometric calibration. Through vacuum radiometric calibration, both the infrared camera and the device for on-board calibration are calibrated. There are several kinds of absolute radiometric calibration after launch, including on-board calibration, radiometric alignment field calibration, and cross calibration between different optical remote sensors. The accuracy of radiometric calibration can be improved through the comprehensive utilization of several calibration methods. In addition, if the on-orbit calibration device changes, it can also be calibrated by other calibration methods such as radiometric alignment field calibration to eliminate system errors, thereby improving the accuracy of on-orbit calibration.

According to the-state-of-the-art technology in China, the on-orbit calibration device is calibrated by vacuum radiometric calibration before the infrared camera is launched, and the calibration accuracy value can reach about ± 1.0 K. After the injection, the state of the on-orbit calibration device of the infrared camera itself may change. In addition, infrared cameras are sensitive to changes in ambient temperature, and the constant change of the external heat flow will affect the working state of the infrared camera, and will have an impact on the calibration accuracy on-satellite. After deducting the system error, it is expected that the calibration accuracy on orbit will not exceed ± 0.5 K, and the accuracy of the on-board calibration can be controlled within ± 1.5 K.

4.8 Application of Infrared Remote Sensing Satellite

4.8.1 Application of Water Pollution Monitoring

Infrared remote sensing can be applied to remote sensing monitoring of key water pollution sources, water blooms, red tides and oil spills, and drinking water sources. It mainly includes water thermal pollution, factory sewage discharge (especially at night), water quality (chlorophyll, water transparency, suspended matter concentration) of main river and estuary, safety of drinking water source, thermal discharge of nuclear power plant, and other high-precision monitoring requirements. Especially high-resolution (better than 10 m) infrared remote sensing has obvious effect on sewage discharge and water thermal pollution monitoring in factories and enterprises.

Since the difference of river temperature near the discharge point, thermal infrared images with high spatial resolution and temperature resolution can effectively detect this abnormal situation for the sewage discharge mostly occurring at night, thus realizing the monitoring of sewage discharge. As shown in Fig. 4.20, the night infrared image of a city shows that the temperature of rivers and urban areas is higher at night, i.e., the high brightness. The abnormal phenomenon that the temperature of sewage discharged by factories is higher than that of rivers is obvious in the picture.



Fig. 4.20 Sewage discharge monitoring map (spatial resolution 10 m)

4.8.2 Urban Infrared Remote Sensing Application

The inversion of surface temperature in Beijing using 10 m infrared images by the Institute of Remote Sensing of the Chinese Academy of Sciences is shown in Fig. 4.21. As can be seen from the map, the temperature in urban areas is obviously higher than that in suburban areas. Because of the high spatial resolution, the temperature information of the inner structure of the city can be well depicted, and the road traffic network in the city Beijing can be clearly seen.

The thumbnail map of Beijing National Stadium area is shown in Fig. 4.22 (left: colored composite map by Google Earth, right: 10 m—resolution ground surface temperature distribution map). It can be seen from the map that the temperature of Bird's Nest and Water Cube Stadium in the middle is lower, and the residential areas on the left and right sides are higher, which reflects the thermal insulation

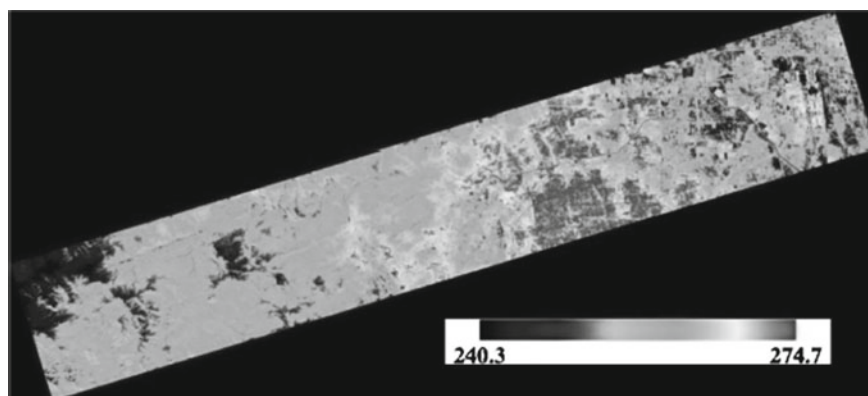


Fig. 4.21 Urban thermal environment application map

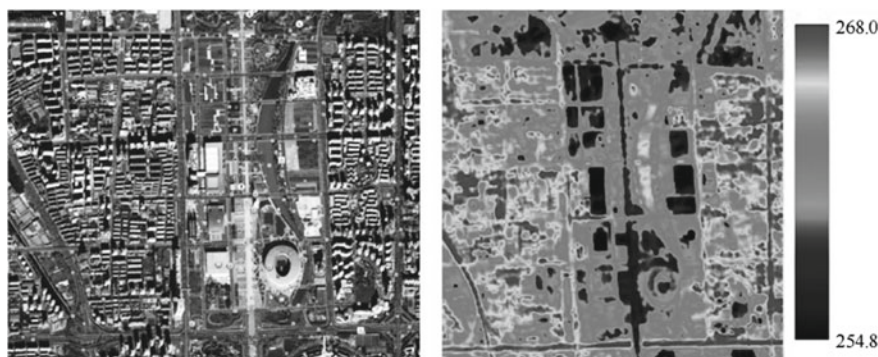


Fig. 4.22 Application map of building energy conservation

performance of the building. In addition, the urban main roads and their thermal characteristics are also clearly visible.

4.8.3 Marine Rights Protection and Regulation Application

With the process of globalization and the deepening of China's foreign economic and trade cooperation, China's development strategy is gradually moving toward "the deep blue." At the same time, the historical problems of marine rights and interests and island management are becoming increasingly prominent. There is an urgent need for real-time awareness of marine situation and sea target tracking, sea surface search and rescue, smuggling, and piracy positioning. China's sea area is vast, while the sea surface targets are relatively small. Ground radar and other means are limited by the detection range to search, locate, and examine targets in wide sea area. Aviation means such as early warning aircraft are also limited by the coverage ability. Visible light spectral band is limited by time, weather, and other factors. By infrared remote sensing with the characteristics of round-the-clock imaging the temperature changes left on the surface of the sea by sailing can be monitored, the route can be distinguished, the ship can be detected, located, and recognized with high-resolution visible light image, thus effectively improving the efficiency of marine supervision.

Ships and their trajectories are clearly visible in high-resolution infrared images as the propeller rotates on the surface of the sea, causing the seawater of low level and low temperature to be agitated to the surface. Figure 4.23 shows the ship and its

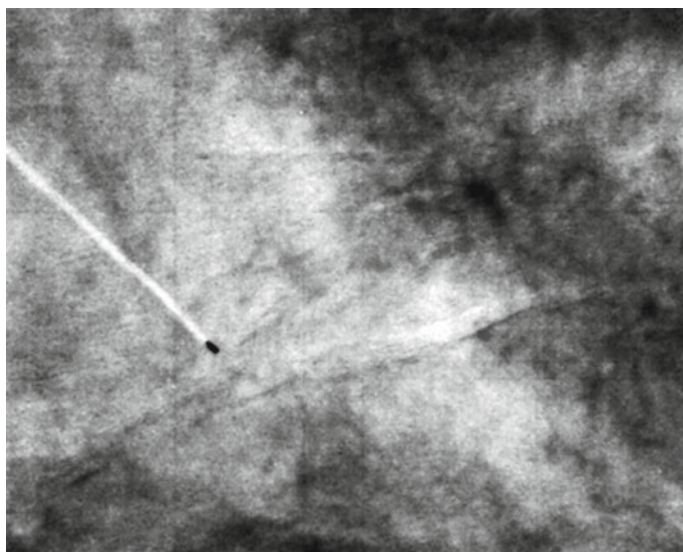


Fig. 4.23 Application map of marine rights protection

track captured by the thermal infrared image with a resolution of 10 m, in which the size of each ship and its course can be distinguished, and then the type, source, and course of the ship can be approximately determined.

4.8.4 National Security and National Defense Application

With the advantage of special imaging spectrum, infrared imaging can not only acquire the contour information of the target, but also acquire the temperature information, so as to identify the working state of the target. Since infrared remote sensing images the temperature information of the scene, its imaging is not limited by time conditions and it can work without light, which is incomparable for visible light cameras. By interpreting the long-wave infrared on-orbit image data of satellite infrared cameras, the information of underground oil depots, oil storage tanks in refineries, working conditions of steelmaking plants and power plants can be identified, and the state of strategic material reserves and war potential can be evaluated. The ship trail, some even up to tens of kilometers, can also be clearly identified from the infrared images, by which the tactical evasion action of the identified ship can also be detected. Temperature imaging can be achieved by infrared imaging, which can realize all-day imaging and improve imaging efficiency. For the military application, the infrared remote sensing can be used

- (1) to increase the number of imaging on target at night and improve the battlefield night dynamic surveillance capability;
- (2) to reveal the camouflage of the target and improve the ability of target recognition;
- (3) to monitor the change of targets and strengthen the capability of battlefield state surveillance;
- (4) to confirm target properties and improve the target recognition rate in combination with visible remote sensing image;
- (5) to increase the imaging capability through smoke over battlefield and improve the efficiency;
- (6) to obtain the damage of enemy ships such as explosion and fire, and evaluate the attack effect.

4.8.5 Application of Visible—Infrared Remote Sensing Fusion

The single means of visible light or infrared remote sensing has limited informational dimensions for acquiring targets, and each has its own advantages and disadvantages. The application efficiency can be greatly improved by using both visible light and infrared method, especially the two methods can simultaneously acquire the target

Table 4.9 Advantages of visible—infrared remote sensing fusion applications

Sensor type	Main advantages	Disadvantages of single sensor
Visible light	High spatial resolution, clear details such as edge texture of ground targets in scene and strong anti-jamming ability are beneficial to distinguish geometric characteristics of military targets	The band information is single and easily affected by natural conditions such as illumination, rain, cloud, and fog
Infrared	Infrared remote sensing has unique advantages in revealing camouflage. Traditional camouflage cannot avoid the infrared radiation difference between target and background. In addition, infrared imaging system can penetrate smoke, detect potential targets hidden in shadows, bushes or camouflage, and has the characteristics of long-range detection and all-weather work	Infrared images are grayscale images with low dynamic range, blurred levels, low clarity, and lower signal-to-noise ratio than ordinary visible images, which is not suitable to eye discrimination. Infrared images are affected by detector nonuniformity, and there are fixed pattern noise, crosstalk and distortion, etc

images and then get the fusion image, which can greatly improve the application performance. For details, see Table 4.9.

The imaging characteristics of the following images can be seen from Fig. 4.25.

4.9 Summary

With the development of remote sensing technology, infrared remote sensing has become an important means of space-based remote sensing. Spatial resolution is an important indicator reflecting the interpretability of remote sensing images. The spatial resolution of infrared remote sensing satellites is expected to be further improved with the improvement of the processing and grinding of optical elements, the optical system adjustment level, and the size and performance of infrared detectors. Infrared focal plane detector technology is the main bottleneck of the development of space infrared remote sensing system and the key technology to achieve high resolution, high sensitivity, and long life infrared remote sensing. Therefore, it is of great significance to accelerate the development of high performance and long array infrared detectors in China. Multi-band infrared remote sensing technology is an important direction of remote sensing application in the future. The radiation characteristics of different ground objects at different temperatures are quite different in different bands. The development of short, medium, and long bands of integrated infrared remote sensing can greatly improve the application efficiency.

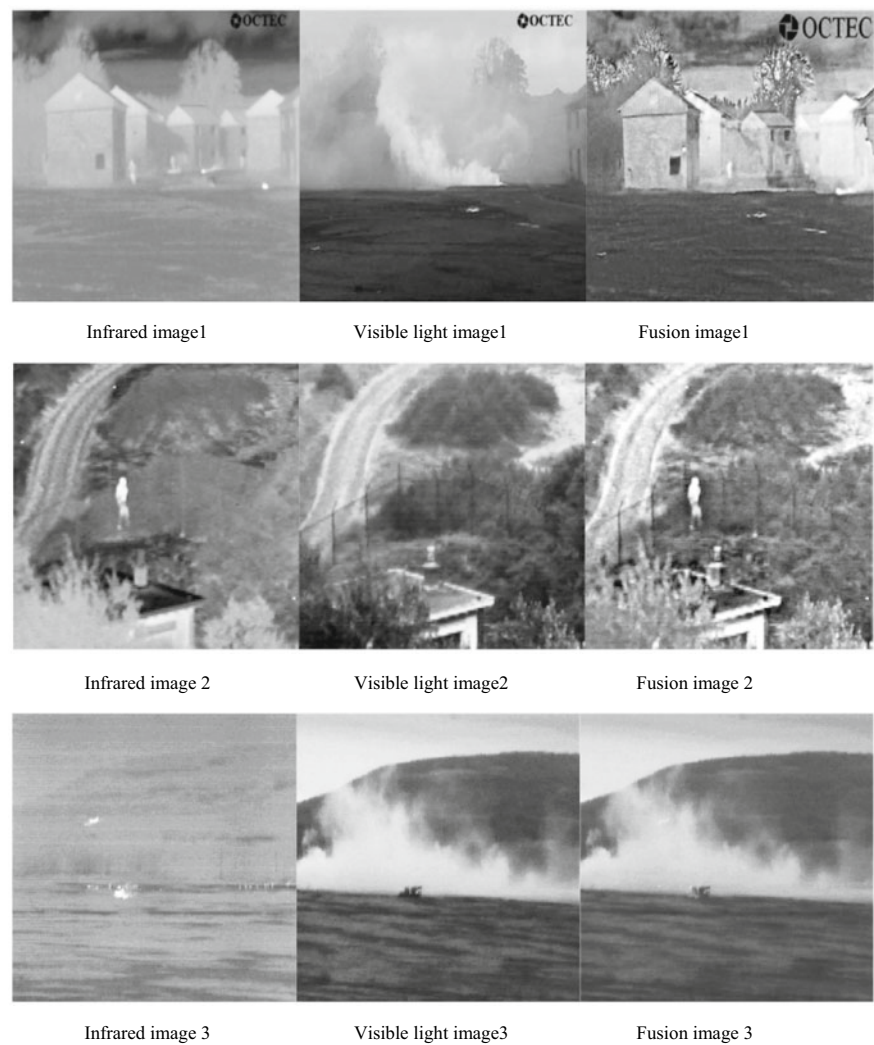


Fig. 4.25 Images by infrared, visible, and fused remote sensing

Chapter 5

Design and Analysis of Hyperspectral Remote Sensing Satellite System



5.1 Overview

Hyperspectral is generally defined as the spectral resolution that is higher than $1/100$ of wavelength. Hyperspectral could be reserved for interferometer type imaging sensors with a very fine spectral resolution. The hyperspectral remote sensing system mainly in visible and infrared spectral bands can acquire the spatial size and distribution information of the target. In addition, it can accurately depict the “continuous” electromagnetic spectral reflection characteristics of ground objects in narrower and denser imaging bands. This imaging method, which simultaneously obtains spatial and spectral information of objects, is called “imaging spectroscopy.” Hyperspectral remote sensing system is one of the most effective space remote sensing systems for monitoring the dynamic changes of the Earth’s environment and quantitative retrieval by remote sensing. It is widely used in the fields of Earth science and applications, deep space exploration and security and defense.

Combining with the development and application of hyperspectral remote sensing satellite system, this chapter focuses on the characteristics of space-borne hyperspectral remote sensing technology and the overall design method suitable for hyperspectral application requirements, including the elements for overall design, hyperspectral imaging quality analysis, system simulation and verification, radiometric and spectral calibration, hyperspectral image processing and application, etc.

5.1.1 Development Review

Space-borne hyperspectral imaging technology was developed on the basis of the airborne imaging spectrometer technology which rose around the 1980s. From the late 1990s, hyperspectral imaging technology began to intrude from airborne system to space-borne system. Table 5.1 shows the technical performance of some global space-borne hyperspectral remote sensing systems in recent 20 years.

Table 5.1 Technical performance of some space-borne hyperspectral remote sensing systems

Instruments	FTHSI	LAC	Hyperion	CHRIS	HIS	ARTEMIS	HIS	AHIS	ISS
State or institution	USA	USA	USA	ESA	China	USA	China	China	Germany
Satellite name	Mighty-Sat II	EO-1		PROBA-1	HJ-1A	TacSat-3	Tiangong-1	Gaofen-5	DEGIS
Launch time	2000	2000		2001	2008	2009	2012	2018	2018
Working band/ μm	VNIR	0.9–1.6	0.4–1.0	0.4–1.05	0.45–0.95	0.4–2.5	0.4–2.5	0.4–2.5	0.4–1.0
	SWIR		0.9–2.5						
Number of spectral channels	VNIR	256	220	18/62	115	>200	128	300	235
	SWIR								
Spatial resolution/m	VNIR	250	30	17/34	100	4	10	30	10
	SWIR		30						
Width/km	7–29	185	7. 7	14	50	20	10	60	30
Orbital height/km	547	705	705	830	499	420–449	400	705	345

The most successful civilian hyperspectral satellite is EO-1 in the United States (launched in 2000). Its on-board imager Hyperion with a spatial resolution of 30 m is a milestone of the space-borne hyperspectral imager, with a visible-near-infrared channel of 0.4–1.0 μm and a shortwave infrared channel of 0.9–2.5 μm . The main mission of satellite EO-1 is to verify the technology of on-orbit hyperspectral imager, evaluate the Earth observation ability of on-board hyperspectral imager, acquire a large amount of precious data, and show the information acquisition ability of space-borne hyperspectral imaging spectroscopy technology to technicians and decision-makers in remote sensing field all over the world.

The space hyperspectral programs launched by the United States include LEWISm NEMO (by the US Navy), OrbView-4, Mighty-Sat II, and TacSat-3. TacSat-3 (launched in 2009) is the most successful hyperspectral satellite in the United States. The spatial and spectral resolution of the hyperspectral imager ARTEMIS onboard TacSat-3 reached at 4 m and 4 nm, respectively. With the idea of large swath design, the United States proposed the project “Decadal Survey,” the hyperspectral satellite HypIRI, to achieve hyperspectral survey with near 30 m spatial resolution and 200 km swath width.

The development of hyperspectral remote sensing system has its own rules. At present, all countries are developing their own new generation of hyperspectral satellites, including the Italian mission PRISMA, the German mission EnMap, and the Japanese satellite HISUI. They mainly focus on satellite with the spatial resolution of 30 m, which is mainly for civil use, and are committed to improving the quantitative application level of hyperspectral data. French military and civil hyperspectral satellite project HYPXIM has a spatial resolution of 8 m in visible-near-infrared band and 8 m in shortwave infrared band. The Italian project SHALOM has a spatial resolution of 10 m in visible-near-infrared band, 10 m in shortwave infrared band, and is equipped with a panchromatic camera with 2.5 m spatial resolution.

The development of space-borne imaging spectrometer technology in China is relatively lagged, but has been promoted rapidly. China launched its first hyperspectral mission, HJ-1A, in 2008, which was mainly used for ecological monitoring. Its spectral coverage ranges from 0.4 to 1.0 μm and the spatial resolution is 100 m. In recent years, the hyperspectral imaging payloads with spectral coverage range from 0.4 to 2.5 μm and the spatial resolution range from 10 to 30 m have been successively carried on China’s space laboratory Tiangong-1 and satellite GF-5, which have promoted the rapid development of the fine and quantitative application of hyperspectral remote sensing in China.

5.1.2 Development Trend

- (1) **Common development of hyperspectral remote sensing technology with different spectroscopic systems.** The development of hyperspectral remote sensing system depends on many factors, such as development level of optical processing and detector manufacture. The grating-based space-borne

hyperspectral imager has been greatly developed in the United States based on the mastered key technology of convex blazed grating. Europe is committed to improving the development of optical system design of prism spectroscopy to make up for the shortcomings of prism spectroscopy, so that the imaging quality has reached the level of the spectrometer of the convex grating, which is popular in the United States.

- (2) **Application field subdivision, customized imaging spectrometer according to user's needs.** Hyperspectral remote sensing system has the advantages of very high spectral resolution and broad application prospects in various fields, covering vegetation monitoring, geology, forest and agriculture, and national defense security, etc. The subdivision of the application fields may promote the development and popularization of hyperspectral imaging technology.
- (3) **Hyperspectral remote sensing technology is developing toward higher spatial resolution and more spectral bands.** In the field of national defense security, there is a strong demand for fine hyperspectral detection with higher efficiency than that of panchromatic or multispectral detection. Hyperspectral data with higher spatial resolution contain more "pure pixels," which greatly reduce the difficulty of endmember extraction and ground objects classification. In addition, broadband hyperspectral detection is also urgently required. In the future, hyperspectral satellites are expected to cover wider spectral ranges and have the ability of on-orbit band selection and dumping.

5.2 Requirement Analysis and Technical Characteristics

5.2.1 Mission Requirement Analysis

In the field of agriculture and forestry, hyperspectral remote sensing technology is used for detailed classification of crops, monitoring the growth of crop and productivity prediction; in the field of ecological application, hyperspectral remote sensing is used to extract biochemical parameters of vegetation and monitor long-term forest health at large scales.

In the application of environmental protection, hyperspectral remote sensing technology has great potential in monitoring the ground surface biophysical parameters, such as atmospheric pollution gases, greenhouse gases, water pollution sources, water quality parameters, and safety of drinking water sources, as well as biodiversity monitoring and soil pollution of ecological environment, soil/moisture, and growth vigor of vegetation.

In the application of disaster prevention and mitigation, hyperspectral remote sensing technology plays an important role in identifying disaster features and predicting the development trend. In the event of a hazard, the information obtained by hyperspectral technology can provide technical support to decision-making departments to better serve disaster prevention and mitigation.

In the field of national security, imaging spectroscopy technology can greatly improve the detection and recognition ability of small targets and low-contrast targets in complex environment and cluttered echo background. It can solve not only the “existence” problem of the observed targets, but also the “what is it” problem of the targets, and become a sharp tool in the field of military and defense security.

The mission requirements analysis for hyperspectral remote sensing system is summarized in Table 5.2.

5.2.2 Target Characteristic Analysis

According to the characteristics of the detection mission, the target characteristics analysis of hyperspectral remote sensing system mainly covers the following categories, as shown in Table 5.3.

5.2.3 Technical Characteristics of Hyperspectral Remote Sensing Satellite

The main technical characteristics of hyperspectral remote sensing satellites are listed as follows:

- (1) **It is difficult to achieve high spatial resolution by hyperspectral technology**
Since hyperspectral technology subdivides the spectral ranges, the energy of the subdivided spectral ranges is very weak, which could be very tough on the realization of high-spatial resolution hyperspectral remote sensing. At present, the spatial resolution of hyperspectral satellites in the civil field is generally 30–60 m. In order to achieve higher spatial resolution, the hyperspectral remote sensing system often requires a strong motion compensation capability of payload or satellite platform to prolong exposure time, increases the energy of subdivided spectrum and ensures the sensitivity of target imaging.
- (2) **Low-temperature environment is required for infrared hyperspectral bands**
For hyperspectral bands in shortwave, medium-wave or longwave infrared segment, the detector shall be cooled to 80–150 K by the on-orbit refrigerator to suppress the thermal noise of detector. In order to meet the long service life requirement of satellite on-orbit, refrigerator shall have the ability to work on-orbit for a long time.
- (3) **High-fidelity massive hyperspectral data compression technology**
The hyperspectral data is a three-dimensional data cube, which brings great pressure to satellite-to-Earth data transmission and ground data processing. In order to avoid the “dimension disaster” of hyperspectral data, hyperspectral satellites

Table 5.2 Mission requirements analysis of hyperspectral remote sensing system

Application type	Mission requirements
Agro forestry	Detailed classification of crops, growth monitoring and productivity prediction, extraction of biochemical parameters of vegetation, monitoring of forest health status
Ecology	Investigation on vegetation ecology, terrestrial ecology and shallow sea ecosystem
Atmospheric detection	Monitoring of pollution gases and greenhouse gases, providing global mapping of aerosol index
Hydrology	Inland water quality monitoring and retrieval of water quality parameters
Geological prospecting	Providing more informative geological maps to detect landslides
Urban environment	Investigation of urban features, detection and analysis of urban light sources, detection of fire sources in urban disasters and detection of chemical and harmful gas leakage, etc.
Disaster detection	Environmental pollution investigation, volcanic eruption and forest fire warning, and chemical and biological toxic gas detection by longwave infrared hyperspectral
Battlefield environment detection and perception	Quantitative detection and analysis of battlefield light sources and minerals, detection of real temperature and emissivity of targets, detection of frequency mixing and frequency doubling of basic frequency vibration of water-bearing minerals, monitoring of urban terrorist attacks
Exposure of camouflage stealth targets on the ground	Disclosure of land camouflage net and infrared stealth of surface warships; recognition of military vehicles, camouflage, submarines, and other artificial materials under complex background conditions
Battlefield detection in shallow sea offshore	Naval vessel detection; detection of beach attributes and water content to provide information support for landing operations; medium and longwave infrared hyperspectral can be used for missile early warning and detection

should be able to compress data on-orbit at high-fidelity level. By implementing compression algorithms or on-orbit spectral programming methodology, the data amount can be reduced on the premise of ensuring spectra quality.

Table 5.3 Analysis of target detection characteristics of hyperspectral remote sensing system

Application type	Basic requirements	Spectral range/ μm	Spectrum resolution/nm	Space resolution/m
Vegetation	Identification of vegetation attributes of economic crops, identification of vegetation height, identification of high grassland and general grassland, and identification of vegetation characteristics	0.49–0.53, 0.55–0.58, 0.67–0.74	5	30–50
		0.40–0.51, 0.53–0.56, 0.58–0.67, 0.78–0.90	10	
		0.90–2.50	20	
Soil rock	Detection of rock types, soil-forming minerals, soil water content, soil granularity, and soil organic matter content	0.48–0.55, 0.6–0.8, 0.9–1.0	10	30–100
		1.35–1.45, 1.85–1.95, 2.10–2.45	20	
Artificial features	Distinguishing high-rise buildings from prominent buildings, strictly distinguishing road types and grades, determining soil quality, identifying the nature of factories and mines, distinguishing building materials, etc.	0.40–0.52, 0.63–0.74, 0.76–0.80, 0.86–1.10	10	5–10
		1.35–1.45, 1.85–1.95, 2.30–2.45	20	
Land water glaciers	Distinguishing perennial rivers with water from seasonal rivers, identifying the location of water level and shoreline, determining the location of rivers flowing underground, identifying artificial ditches, monitoring water quality, and confirming the glacier range line	0.6–0.7, 0.55–0.57, 0.68–0.71, 0.76–0.82, 1.00–1.15, 2.1–2.3	5	10–30
		Other bands in the range of 0.40–2.45	10	

(continued)

Table 5.3 (continued)

Application type	Basic requirements	Spectral range/ μm	Spectrum resolution/nm	Space resolution/m
Marine element	Accurately identifying coastline, distinguishing coastal properties, identifying beach properties and scopes, identifying rocks uncovered and reef submerged rocks, distinguishing harbor use types and building materials, detecting coastal bottom properties, marine environment survey, marine resources development, shallow water depth inversion, coastal topographic mapping	0.4–0.7, 0.7–1.0	5–10	5–30
		1.0–2.5	20	
Military detection	Real temperature and emissivity of detecting targets, infrared stealth exposure of surface ships, missile early warning detection, toxic gas detection	0.4–1.7, 3–5, 8–12	0.2–5	>30
	Disclosure of land camouflage net and identification of military vehicles, camouflages, submarines, and other artificial materials under complex background conditions	0.4–1.2, 1.2–2.5	5	2–10

(4) **Multiband-shared optical path design, including visible-near-infrared, shortwave infrared, medium-wave infrared, and longwave infrared high spectra**

With the development of relevant technology, the registration accuracy of the spectrum segment is greatly improved, and the common optical path design is performed for visible-near-infrared, shortwave infrared, medium-wave infrared,

longwave infrared high spectra, and PAN, thereby achieving higher precision for fusion matching.

5.3 Key Performance Indices and Implications of Imaging Quality for Hyperspectral Remote Sensing System

5.3.1 Radiation Imaging Quality

The hyperspectral remote sensing system obtains spatial-spectral-integrated data. The spatial scale of hyperspectral remote sensing system is to obtain clear radiance image with high spatial resolution, which can be easily interpreted by human eyes. The image quality mainly depends on the following key indicators.

- (1) **On-orbit MTF** is an indicator to evaluate the on-orbit spatial resolution of imaging system. The higher the on-orbit MTF is, the better the imaging quality of the system. It is mainly determined by the static transmission function of imaging spectrometer, atmospheric condition, attitude stability of satellite platform, micro-vibration on-satellite, correction accuracy of deviation angle, and stability of on-orbit space environment.
- (2) **SNR and NETD** reflect the sensitivity of imaging system. The better the SNR and Noise Equivalent Temperature Difference (NETD), the smaller the image noise.
- (3) **Dynamic range** refers to the ability of an imaging system to record the brightest and darkest details and recognition levels. The better the dynamic range of the system, the more detail the image is obtained and the richer the sense of layer is. It is mainly affected by the response characteristics of the detector and the gain characteristics of imaging electronics.
- (4) **Frame rate**. The hyperspectral system uses the area array detector, and the instantaneous image obtained by the area array is called a frame. Corresponding to the index line frequency of the general visible light camera, the hyperspectral system uses the index frame rate to specify the image shift matching relationship between the satellite and the ground. In general, the frame rate should be adjustable on orbit, that is, it should be adapted to the requirements of satellite imaging in all pointing ranges of orbit altitude and direction.

Unlike common visible light camera, the on-orbit MTF, NSR, NETD, and dynamic range of hyperspectral remote sensing system shall be calculated and averaged one by one for the subdivided single-spectral channel, and output as a result of evaluating the on-orbit radiation performance of the hyperspectral remote sensing system.

5.3.2 *Spectral Quality*

The spectral scale of hyperspectral remote sensing system is to obtain accurate continuous spectral curves and its image quality mainly depends on the following:

- (1) **Spectral range** reflects the maximum spectral response range of the imaging system, which is mainly determined by the spectral response characteristics of detector.
- (2) **Spectral resolution** refers to the position of the central wavelength and the bandwidth of each spectral band, which reflects the spectral detection ability of hyperspectral imager. It is mainly determined by the size of spectrometer and detector.
- (3) **Spectral sampling interval** reflects the wavelength sampling interval between the two adjacent spectral bands, which is generally $1/1.1-1/2$ of the spectral resolution.
- (4) **Radiometric calibration accuracy** determines the spectral line amplitude accuracy of hyperspectral response curve, which is divided into relative radiometric calibration accuracy and absolute radiometric calibration accuracy. The relative radiometric calibration accuracy mainly includes the residual of the response inconsistency correction of the detection unit and the error induced by nonuniformity and instability of integral sphere output. The absolute radiometric calibration accuracy is to determine the spectral response function of all detection units. After the relative radiometric calibration, the absolute calibration coefficients of each pixel in the spectral dimension should be identical.
- (5) **The accuracy of spectral calibration** determines the accuracy of peak position of hyperspectral response curve, which mainly depends on the sensitivity and stability of hyperspectral imaging system.
- (6) **Spectral restoration/compression quality** refers to the fidelity of scene image after compression, decompression, and spectral restoration relative to the original scene image, which is mainly affected by compression algorithm and spectral restoration. Generally, spectral shape similarity and deviation of spectral amplitude can be used to characterize the variation of spectral characteristics. Spectral Angle Mapping (SAM) and Relative Quadratic Error (RQE) are used to evaluate the similarity of spectral shape and the deviation of spectral amplitude, respectively.

In addition, SNR and NETD also affect the spectral quality to a certain extent.

5.3.3 *Geometric Imaging Quality*

In order to meet the application requirements, it is also required that hyperspectral images have high geometric accuracy, which includes

- (1) **Ground pixel resolution** refers to the geometric size of the detector unit projected to the ground through the photographic center, which is determined by the focal length of the optical system of the spectrometer, the size of the detector unit, and the altitude of the satellite orbit.
- (2) **Swath** refers to the ground width that an imaging system can cover. For push-broom or gazing systems, the swath is determined by the FOV angle of the optical system.
- (3) **Geometric positioning accuracy** refers to the errors between the image positioning of the observed ground objects and their actual geographical position, which are determined by satellite attitude determination, orbit determination, time synchronization accuracy, the principal points, principal distances, and distortion of the imaging spectrometer, etc.
- (4) **Image distortion** refers to the extrusion, extension, migration, and distortion of the geometric spatial relationship between the observed ground objects relative to the actual spatial relationship on the ground, which is determined by the motion of the satellite platform, the distortion of the optical system of the spectrometer, the scanning performance, and the correction of the deviation angle, etc.
- (5) **Spectral registration accuracy** refers to the degree of agreement between ground homologous point pixels imaged by multiple spectral channels of hyperspectral imaging system, which is determined by factors such as the spectrum boresight angle difference, attitude stability, attitude sampling frequency, and so on.

5.4 Design and Analysis of Imaging Quality of Hyperspectral Imager

5.4.1 Analysis of Key Design Elements of Hyperspectral Imaging Quality

The main technical specification of hyperspectral remote sensing satellite is directly relative to the quality of data acquired by users. The key design elements of imaging quality mainly include the selection of imaging system, optical system design, spectral range selection and configuration, detector design, ground pixel resolution, imaging swath, frame rate characteristics, on-orbit dynamic MTF, dynamic range and SNR, compression algorithm, spectral registration accuracy, attitude accuracy and stability, motion compensation, etc.

5.4.2 Selection of Imaging System

According to the different imaging modes, hyperspectral imager can be divided into two types: sweeping type with linear array detector and push-broom type with area array detector, as shown in Fig. 5.1.

The sweeping type hyperspectral imager with linear array detector has the advantages of large FOV, fine pixel registration accuracy, and real-time calibration. The disadvantage is that the exposure time of each detection unit is short. It is difficult to further improve spectral resolution and radiative sensitivity, so that it is often used on airborne platforms with relatively low velocity.

The advantages of push-broom type hyperspectral imager with area array detector are the high relative sensitivity and high spatial resolution, e.g., in the visible light band, its spectral resolution can reach 4–10 nm. Because of the high velocity of the solar synchronous orbit satellite platform (about 7 km/s), it is difficult to realize high spatial resolution for space-borne hyperspectral imager systems. Therefore, push-broom imaging is widely used, but its FOV is limited.

According to different light-splitting modes, space-borne hyperspectral imaging systems can be categorized into two classes: dispersive spectroscopy and interference spectroscopy. Dispersive hyperspectral imager has the characteristic of intuitive image data. It can be divided into prism spectroscopy and grating spectroscopy according to the different spectroscopic elements. Prism and grating dispersive imaging spectrometers appeared earlier and their technology is relatively mature. Many aerospace imaging spectrometers adopt such spectroscopy technology, including the Hyperion by the United States. The target signals are split into two coherent beams by the interferometric spectroscopic hyperspectral imager, the optical path difference is modulated between two coherent beams, the coherent results of different optical path differences are sampled, and the sampled interferogram is

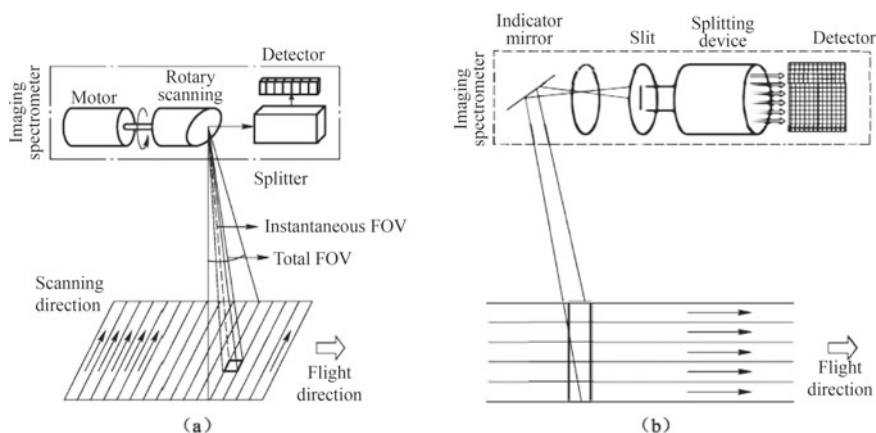


Fig. 5.1 Several spatial scanning modes of hyperspectral remote sensing. **a** Sweeping type; **b** push-broom type

converted by Fourier transformation to obtain the target spectral information. Interferometric spectrometer has become a new development direction in the light of its unique characteristics.

5.4.3 Design of Spectrometer Optical System

The key to the design of hyperspectral optical system lies in the spectral-splitting modes. According to the different spectral-splitting modes, it can be divided into two categories: dispersive spectroscopy and interference spectroscopy. The dispersive spectroscopy can be subdivided into prism spectroscopy and grating spectroscopy.

5.4.3.1 Design of Dispersive Optical System

Dispersive optical system is with prism or grating splitting subsystems in collimating beams, as shown in Fig. 5.2. The incident slit is located on the front focal plane of the collimating system. After the incident light passes through the collimating mirror, it is imaged on the focal plane detector by prism or grating splitting.

The spectrum obtained by prism dispersion is nonuniform but with the high energy. It is applied in European hyperspectral satellites Proba-1 and EnMap. The advantage of grating type splitter is that the spectrum is uniform and the data is intuitive. The performance of grating dispersion and spectroscopy depends on the performance of the selected grating. With the improvement of fabrication technology and performance of convex grating (e.g., Hyperion), high SNR can be easily obtained in shortwave band.

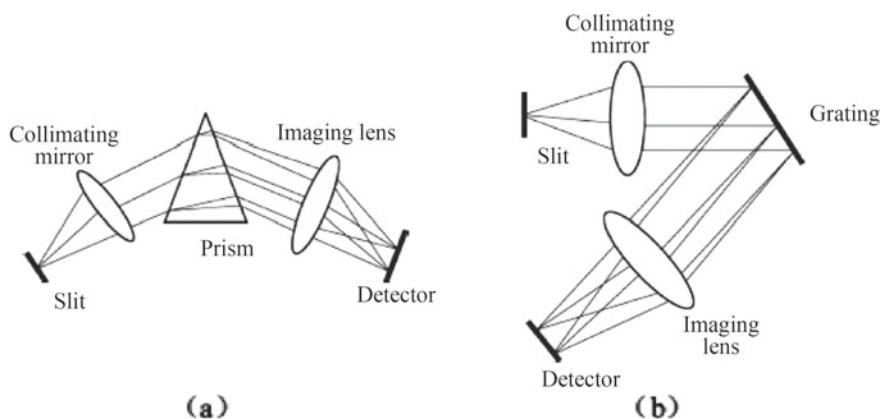


Fig. 5.2 Design of dispersion optical system with prism/grating splitter. **a** Prism splitter for collimating beam; **b** grating splitter for collimating beam

5.4.3.2 Design of Interferometric Optical System

The interferometric spectrometer can be divided into three types according to the modulation mode: temporal modulation, spatial modulation, and spacial-temporal joint modulation. The designs of these three types of optical systems are shown in Fig. 5.3a–c, respectively.

(1) Temporal modulation

The most classical interferometric hyperspectral imaging spectroscopy is a (dynamic) time-modulated interferometric spectrometer based on the principle of Michelson interferometer, by which the target interferometric data is acquired by the moving

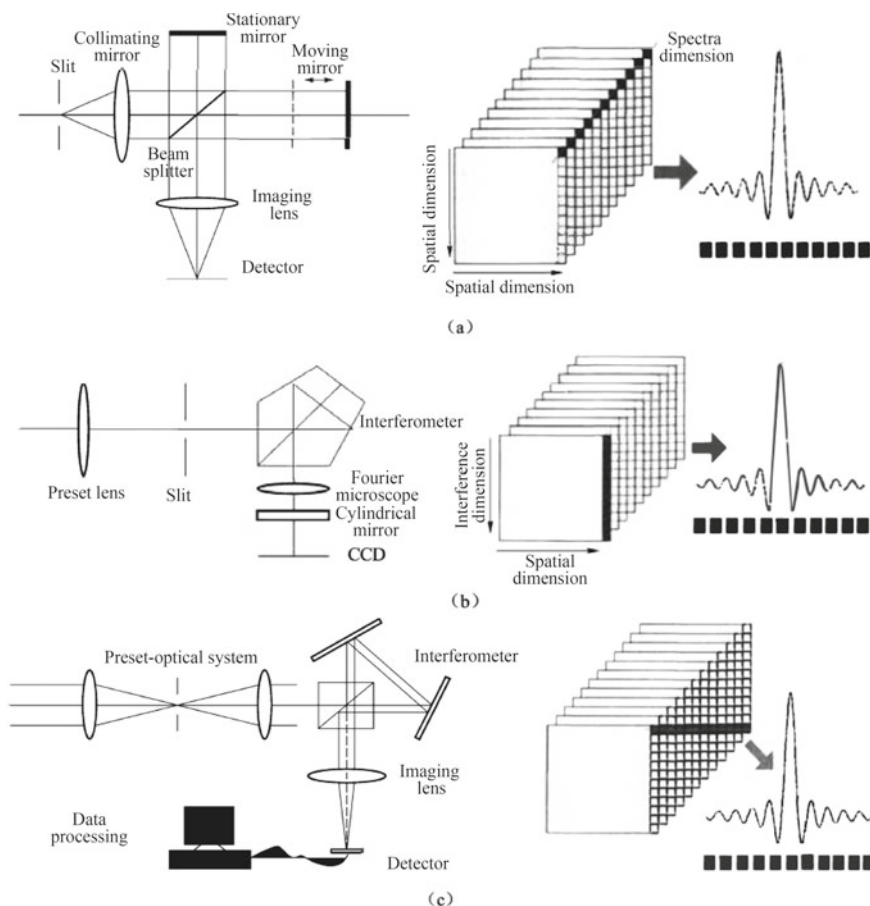


Fig. 5.3 Design of interferometric optical system. **a** Principle diagram of time-modulated interferometric spectrometer; **b** principle diagram of space modulated interferometric spectrometer; **c** principle diagram of space-time jointly modulated interferometric spectrometer

mirror scanning to form different optical path differences. The same spatial point data of all interference image frames in a scanning period constitute the interference data of this point.

This spectral imager has high sensitivity and fine spectral resolution, and is especially suitable for atmospheric sounding applications requiring spectral bands ranging from hundreds to thousands. However, the dynamic interferometric spectrometer requires a highly stable and precise moving mirror system, and it is difficult to achieve high spatial resolution imaging for solar synchronous orbit platform.

(2) Spatial modulation

Spatially modulated interferometric imaging spectroscopy is realized by adding interferometer to a wideband optical imaging system. It imagines a point target, and a beam is cut into two beams in parallel after the interferometer. An interferogram with one-dimensional space and one-dimensional spectrum is formed on the detector, and another one-dimensional space is formed by the push-broom of the instrument. This interferometry avoids the difficulty of moving mirror, but its energy efficiency is still insufficient for the application requirements of high spatial resolution such as meter level.

(3) Spatial-temporal joint modulation

Spatial-temporal jointly modulated interferometric spectrometer is also known as large aperture static interferometric spectral imager, in which the slit is replaced by FOV aperture, and the optical path difference is modulated by the change of FOV. The interference fringes formed by object in different optical path differences can be obtained by one-dimensional push-broom in space. This method has a high-energy utilization rate, fully guarantees the realization of high resolution and SNR, and is suitable for high-resolution hyperspectral remote sensing observation.

5.4.4 Band Selection and Configuration

5.4.4.1 Spectral Band Selection

Spectral range reflects the ability of sensible spectral range of space-borne hyperspectral imager, which should be determined according to the observation requirements, and the reference requirements of spectral coverage, tolerance, and out-of-band response should be given. Considering the general use of hyperspectral remote sensing, this indicator should cover at least visible-near-infrared ($0.4\text{--}0.9\text{ }\mu\text{m}$) and shortwave infrared bands ($0.9\text{--}2.5\text{ }\mu\text{m}$); considering the development trend of broadband hyperspectral imager, this indicator can also be extended to medium-wave infrared ($3.0\text{--}5.0\text{ }\mu\text{m}$) and longwave infrared band ($8.0\text{--}12.5\text{ }\mu\text{m}$).

5.4.4.2 Spectral Resolution and Spectral Band Analysis

Spectral resolution refers to the position of the central wavelength and the bandwidth of each band, which reflects the ability of hyperspectral imager to detect spectra. For general applications of hyperspectral resolution, the spectral resolution in visible-near-infrared band is 5–10 nm, and that in shortwave infrared band is 20–30 nm. The number of spectral bands directly reflects the ability of space-borne hyperspectral imager to subdivide the spectrum. In general, 60 spectral bands of visible-near-infrared and shortwave infrared bands can meet the requirements of civil and military uses.

For the interferometric hyperspectral imager, in order to achieve a certain spectral resolution, the transverse shear of the interferometer and the focal length of the Fourier mirror should be calculated when designing the optical system. The spectral resolution of the interferometric hyperspectral imager is calculated by Formula (5.1):

$$\left. \begin{aligned} \text{DOPD} &= \frac{d \cdot s}{f_F} \\ L_C &= \text{DOPD} \cdot N_M \\ \delta\lambda_i &= \frac{1}{2 \cdot L_C \cdot \lambda_i} \end{aligned} \right\}, \quad (5.1)$$

where DOPD is the optical path difference corresponding to a single detection unit of the interferometric hyperspectral imager, d is the transverse shear of the interferometer, s is the detector size, f_F is the focal length of the Fourier mirror, L_C is the maximum optical path difference of the interferometric hyperspectral imager, N_M is the number of pixels from the brightest fringe of the interferogram to the edge of the detector, λ_i is the designated restored central wavelength, and $\delta\lambda_i$ is the spectral resolution corresponding to the specified restored central wavelength.

From the above formula, it can be seen that the spectral resolution of the interferometric hyperspectral imager is not uniform and related to the wavelength position. The number of spectral bands can be determined according to the results of spectral image restoration.

5.4.5 Detector Selection

The push-broom type hyperspectral remote sensing imaging system must simultaneously acquire the spatial dimension and the spectral dimension information, and generally uses the area array detector to acquire the target image information. According to the status of the detector development, two kinds of detectors are used from the visible light to the infrared to obtain the ground objects information of different spectral bands. For wideband applications, a CCD detector has also been developed, which ranges from visible light to ultraviolet, even to

near-infrared and mid-infrared. The following describes two typical hyperspectral detectors: visible-near-infrared and shortwave infrared hyperspectral detector.

5.4.5.1 Visible-Near-Infrared Detector

Visible-near-infrared detectors include both CCD and CMOS. At present, the specifications of CCD detectors have developed from hundreds of pixels $\times$ hundreds of pixels to thousands of pixels $\times$ thousands of pixels, and 2048×2048 silicon CCD has been available in market; the frame rate of detectors has grown from tens to hundreds fps.

In order to improve the detection sensitivity of CCD, the Electronic Multiplier CCD (EMCCD) and back-illuminated CCD have been developed following the common-mode CCD. The hyperspectral camera onboard the HJ-1 satellite uses a back-illuminated CCD, which has been verified by on-orbit flight and performs well.

Silicon CMOS detector technology is also very mature in the world. It is not difficult to divide the spectral sampling interval of visible-near-infrared band into 1–2 nm by a silicon CMOS detector. Advanced German hyperspectral imager EnMap with silicon CMOS detector in visible-near-infrared band has fast frame transfer velocity and low readout noise. It is a highly integrated back-illuminated detector with a corresponding spectral range of 420–1000 nm.

5.4.5.2 Shortwave Infrared Detector

The area array Mercury Cadmium Telluride (MCT) detector is most widely used in shortwave infrared hyperspectral imager. At present, a large-scale focal plane detector has been successfully developed and is beginning to be used in practice. The shortwave infrared detector of the satellite EnMap in Germany uses area array MCT+Read Out Integrated Circuit (ROIC) with a quantization efficiency of 60%. The corresponding spectral range is 900–2450 nm, and the area array size is 1024×256 . At present, the infrared detector is mostly integrated with refrigerators due to refrigeration need.

The area array MCT infrared detector has the inherent properties of bad pixels, and because the indium column is connected with the readout circuit made of Si and MCT material separately, the device is subjected to thermal stress impact when it undergoes multiple cold and thermal cycles, which will easily cause the disconnection or breakage of the connection structure, thus resulting in the sensible charge to be unreadable and the increment of bad pixels. Therefore, it is very important to develop a long life, high-reliability refrigerator and further improve the technology of this type of array detector.

5.4.6 Design of Ground Pixel Resolution

The resolution of sub-satellite ground pixels should be determined according to the detection mission. Generally, the spatial resolution of civilian hyperspectral is over 30 m, while military requires higher resolution of pixels. The resolution of sub-satellite point ground pixels is calculated by Formula (5.2) according to satellite orbital height, the center distance between adjacent photosensitive elements (or sampling distance on image plane), and the focal length of hyperspectral imager.

$$\text{GSD} = d_s \times H/f, \quad (5.2)$$

where GSD is the resolution of the ground pixel of the sub-satellite point, d_s is the center distance between the adjacent photosensitive elements of the detector, f is the focal length of the spectrometer, and H is the orbital height of the satellite.

5.4.6.1 Imaging Swath Design and Pixel Number Determination

For push-broom hyperspectral imager, the imaging swath depends on the FOV and orbital height of the optical design, and its sub-satellite point imaging swath can be approximated as

$$W = 2R_e \left\{ \pi/2 - \text{FOV} \cdot \pi/360 - \arccos \left[(R_e + H) \cdot R_e^{-1} \cdot \sin(\text{FOV} \cdot \pi/360) \right] \right\}, \quad (5.3)$$

where FOV is the field of view, R_e is the radius of the Earth, H is the orbital height.

According to the imaging swath and pixel resolution, the number of pixels needed can be calculated. In addition, in the case of on-satellite spectral calibration design, a certain number of pixels will be occupied. For example, a resource satellite hyperspectral imager in China has reserved 7–10 pixels in the length direction of detector array for spectral calibration.

5.4.7 Frame Rate Analysis

In general, the frame rate of hyperspectral imager should be adjustable on-orbit to meet the requirements of satellite orbit altitude and attitude maneuver pointing imaging range. The frame rate corresponding to the highest and lowest orbital heights is determined by simulation calculation, and the frame rate range is then given:

$$\left. \begin{aligned} T_i &= V_g / \Delta L / 1000 \\ V_g &= \left[(2\pi R_e / T)^2 + (2\pi \cdot 86400^{-1} \cdot R_e \cos \Phi)^2 \right. \\ &\quad \left. - 2(2\pi R_e)^2 \cdot 86400^{-1} \cdot T^{-1} \cdot \cos \Phi \cdot \cos i \right]^{1/2} \end{aligned} \right\}, \quad (5.4)$$

where T_i is a frame rate, in frame/s; V_g is the velocity of the sub-satellite point relative to the ground when the satellite is working, that is, the velocity of the sub-satellite point; R_e is the average radius of the Earth, generally 6371.3 km; ΔL is the resolution of the ground pixel; Φ is the design reference latitude; T is the orbit period of the satellite; i is the satellite orbit inclination.

The frame rate is about 705 frames/s at a resolution of 10 m and 352 frames/s at 20 m. When the orbit height is in the range of 460–568 km, the corresponding equivalent ground velocity is 6.95–7.07 km/s; the resolution of the ground pixels corresponding to visible spectrometer is 9.9–11.36 m; the resolution of the ground pixels corresponding to infrared spectrometer is 19.8–22.72 m; therefore, the corresponding frame rate of visible light is 612–713 frames/s, and the corresponding frame rate of infrared is 310–356 frames/s. If parallel sampling technology is adopted, the frame rate can be reduced by half and the infrared frame rate can be reduced to 155–178 frames/s.

The maximum frame rate of the visible light detector can reach 1000 frames/s. Considering the extreme conditions and design margin of satellite orbit altitude change and attitude maneuver, the frame rate range of the visible spectrometer can be designed at 350–750 frames/s, and the frame rate can be adjusted on orbit. The frame rate of infrared detector is generally no more than 200 frames/s. Parallel sampling technology can reduce the frame rate requirement and keep the relationship between infrared frame rate and visible frame rate at 1:4. Considering the extreme conditions and design margins of satellite orbit altitude change and attitude maneuver, the frame rate range of visible spectrometer can be designed in 100–180 frames/s, and the frame rate can be adjusted on-orbit.

5.4.8 Evaluation of On-Orbit Dynamic Modulation Transfer Function

The hyperspectral imager obtains the spatial-spectral-integrated image by pushing-broom with the area array detector. For the dispersive spectrometer, the data cube is directly obtained after light scattering. The on-orbit MTF test method of the selected band image is consistent with that of the traditional TDI CCD visible light image.

For a hyperspectral imager with spatial-temporal joint modulation, a frame of image can obtain two-dimensional spatial interference image with interference information. After extracting the continuous interference image through the compressed encoder of the spectrometer, the transformed interference image with different optical path difference of a certain ground object is formed, and finally transmitted to the ground by data transmission. Because of the particularity of its imaging principle, the evaluation of on-orbit MTF for interferometric hyperspectral imager requires that the interferometric image be reconstructed into an image with “image” information in laboratory and on-orbit measurements before it is evaluated.

5.4.9 Dynamic Range and SNR Evaluation

The indicator of SNR of various imaging spectrometers is usually determined according to the practical application requirements of the satellite. There are great differences in SNR evaluation indicators for different observation applications, such as ocean and land observation. For land observation, because the dynamic range is higher than that of ocean observation imaging spectrometer, the SNR decreases slightly. For NEMO satellite with COIS ocean imaging spectrometer, the SNR (designed value) of visible lights spectrum band can reach 200:1 under the condition of ground pixels resolution of 30 m. Since the spectrometer design is mainly used for ocean observations on relatively low-variable targets, the requirement of dynamic range is also low. The imaging spectrometer Hyperion of the satellite EO-1 in the United States has a SNR of (140–190): 1 under the conditions of resolution of 30 m, the spectral band between 550 and 700 nm, the target reflectivity of 0.3, and the solar altitude angle of 30°.

Hence, at present, there is no universal criterion for evaluating SNR worldwide. The SNR of imaging spectrometer is often assessed in the condition of narrow spectral range or even high at-sensor radiance in a single-spectral band. For example, the hyperspectral satellite EnMap in Germany has an imaging spectrometer with 30 m ground resolution. As for the evaluation of SNR, only 495 nm single-spectral band is evaluated in the visible light spectral band under the conditions of 0.3 target reflectance and 60° solar altitude angle, achieving an SNR of 500:1.

For a high-resolution hyperspectral remote sensing satellite, the average SNR is evaluated over the full spectrum range of 450–900 and 900–25,000 nm, and the assessment conditions are more strict. The key of designing a high-performance hyperspectral remote sensing system is to obtain high SNR spectral images of the target adaptively in different dynamic ranges for different ground objects, thus customized “shooting” typical spectral targets according to practical requirements.

5.4.10 Compression Algorithms and Compression Ratio Configuration

With the continuous improvement of the spatial and spectral resolution of hyperspectral images, the data size of hyperspectral images has been multiplied. For example, an AVIRIS $614 \times 512 \times 224$ hyperspectral image with two-dimensional spatial pixels of 614×512 and 224 bands needs 140 MB of storage space, if the gray level of each spatial pixel is represented with 16 bits. It can be seen that the data size stored in hyperspectral images is generally huge compared with the general visible light remote sensing data. Therefore, for a high-resolution hyperspectral remote sensing system, it is necessary to consider the data compression design on satellite and focus on the maintenance of spectral characteristics after data compression.

For a spatial-temporal jointly modulated interferometric hyperspectral imager, the original image is shown in Fig. 5.4a. Before compression, the spatially redundant information and the spectrally redundant information can be counterchanged by reassigned transformation. Figure 5.4b shows a two-dimensional image with only spatial information, and Fig. 5.4c contains the fringe information with only interference information. By comparing the three images, it can be seen that Fig. 5.4c is smoother and with better compression performance. Before JPEG2000 compressing the spatial-temporal jointly modulated interferogram, Fig. 5.4a should be transformed into the form of a spatially modulated interferogram such as Fig. 5.4c, and then compressed to improve compression performance.

High-ratio compression can achieve real-time compression and data dumping on-satellite. However, certain SNR and spectral quality of data are usually lost under the special characteristics of the image-spectrum merging of hyperspectral data, when high-ratio compression is used. Table 5.4 shows that different compression ratios have different effects on average SNR.

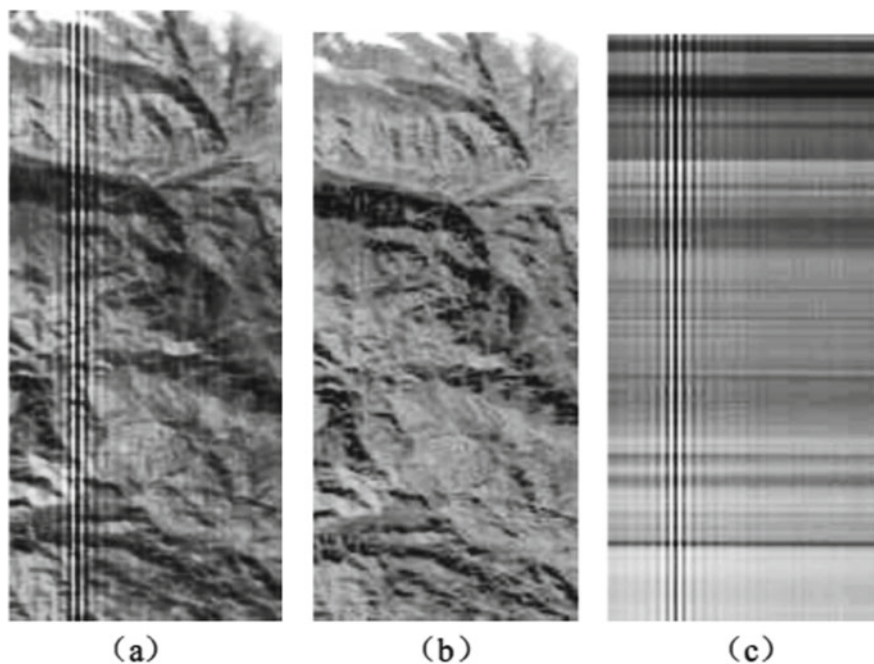


Fig. 5.4 Interferometric hyperspectral images with different assignment formats. **a** Spatial-temporal jointly modulated interferogram of one frame; **b** traditional two-dimensional optical image; **c** spatial modulation interferogram after transformation

Table 5.4 Software processing simulation results of the influence of compression ratio on average SNR of restored spectral bands

Items	Visible spectrometer			Infrared spectrometer		
Compression ratio	No compression	5.7:1	8:1	No compression	2.5:1	8:1
Average SNR/%	100	91.6	87	100	78.6	46.8

Results normalized relative to uncompressed cases

5.4.11 Accuracy of Spectral Registration

For a hyperspectral imager with a single detector, either dispersion or an interference one, the information of all spectral bands in a certain spatial dimension of a pixel is obtained from the same pixel, so there is no spectral mismatch between detectors. However, for those who use multiple hyperspectral imagers to achieve different hyperspectral band images, it is necessary to accurately obtain the to-ground pointing of the two spectrometers. The high-precision optical-mechanical-thermal integration design is adopted on-satellite to ensure the stability of the on-orbit pointing, so as to achieve accurate registration between spectral bands on the ground. Nowadays, more and more hyperspectral imagers adopt common path design, which greatly reduces the difficulty of spectral registration.

5.4.12 Effect of Attitude Stability and Drift Angle Control Accuracy on Recovery Accuracy

For the hyperspectral interferometric imager, the requirement for attitude control of the satellite platform is relatively high because the spectral information is obtained in a time-sharing manner.

5.4.12.1 Attitude Stability

Since the hyperspectral imager uses a continuous multi-frame sampling along the flight direction to obtain an interference image of a complete spectral band of ground objects, the spectral recovery curve of each spectral band is obtained by ground inversion. Therefore, the unstable attitude during the push-broom imaging of the same ground object for multiple consecutive times will cause the interference information of adjacent pixels to be aliased, which will have a certain influence on the spectral restoration accuracy of the ground objects.

Taking the interferometric spectrometer with a 180×1024 detector as an example, the displacement of push-broom of 180 lines is about 0.21 pixels under the attitude stability of 1×10^{-3} °/s. The simulation results of spectral restoration show that the accuracy of spectral amplitude restoration is reduced by about 7%. When the stability

is 5×10^{-4} °/s, the displacement deviation is about 0.1 pixels, and the accuracy of spectral amplitude restoration is decreased by about 3%. This shows that the satellite attitude stability has a great influence on the amplitude of spectral restoration and its quantitative application. By contrast, it has little influence on the spectral similarity and correlation, as well as the qualitative analysis of targets, such as classification and recognition.

5.4.12.2 Control Accuracy of Satellite Drift Angle

The accuracy of drift angle control has a great influence on the spectral restoration accuracy of the hyperspectral imager, especially for a spatial-temporal jointly modulated interferometric imaging spectrometer. It is characterized in that each frame of data contains both spatial information and interference spectrum information. Because of the particularity of imaging principle, in order to obtain the complete interferogram of the target, the target should be continuously imaged in push-broom mode. In the process of acquiring continuous frame data, the corresponding relationship of the same ground object points is fixed. However, due to the influence of drift angle control accuracy, the corresponding ground objects have a lateral offset in hyperspectral imager in the whole FOV and continuous push-broom imaging mode, which will affect the spectral restoration accuracy. For example, assuming that the accuracy of satellite drift angle control is 0.05° , the lateral offset is 0.16 pixels, and the average relative deviation of the restored spectral curve can be controlled at about 3%.

5.4.13 Design of Large Angular Motion Compensation

With the increasing demand for spatial resolution of hyperspectral imaging system, the problem of energy deficiency is becoming more and more serious. Motion compensation using “delayed imaging” is a common design method, that is, the imaging velocity of hyperspectral sensors relative to ground objects is slowed down by means of pendulum-mirror fly-back (such as target aircraft Tiangong-1) of hyperspectral payload or whole satellite attitude (such as satellite TacSat-3) to compensate for its energy deficiency. Usually, the compensation can reach 2–8 times according to the situation of insufficient energy. The motion compensation mode is shown in Fig. 5.5, before imaging, attitude maneuver should be carried out according to the imaging mission to establish the initial yaw angle and the active fly-back attitude angular velocity; imaging parameters should be set, imaging, recording, and transmission should be carried out; after imaging, attitude maneuver should be returned to zero or according to the attitude of the next mission.

Whether it is pendulum mirror or whole satellite attitude fly-back, the following problems should be solved:

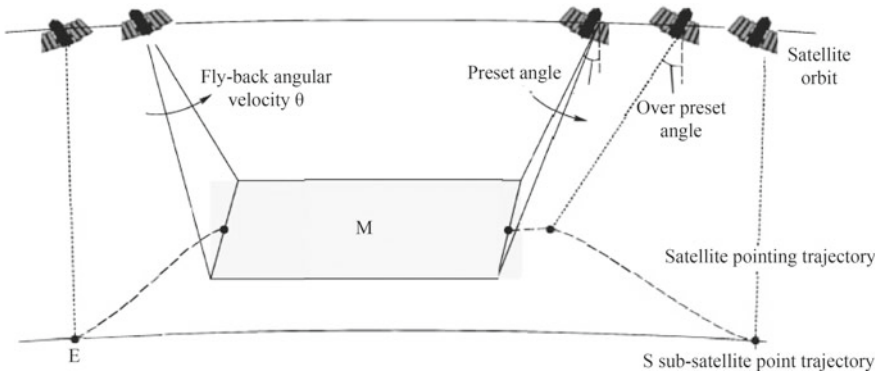


Fig. 5.5 The maneuvering process of motion compensation mode

- (1) **High requirement of the stability of compensation velocity.** In order to adapt to the mission of hyperspectral imager in “backward-scanning compensated dynamic imaging” and ensure high requirement of MTF imaging and multispectral accurate matching imaging missions, high requirements are also placed on the stability of the compensation velocity. For the compensation imaging mode with the whole satellite backward scanning, the attitude velocity fluctuation of the satellite fly-back compensation process shall be small.
- (2) **High requirement of the compensation pointing measurement and control accuracy.** For active backward-scanning compensation imaging mode, high-dynamic star sensor or high-precision pendulum-mirror pointing measurement equipment are required to match its high-precision imaging pointing control.
- (3) **High requirement of satellite agility.** The backward-scanning compensation imaging greatly affects the application mode of hyperspectral imaging system “elongated strip,” so it is more suitable for “point target” imaging satellite. However, in order to obtain ground target information as much as possible within a single orbit, the satellite must have fast, smart, and agile maneuverability.

5.4.14 High-Precision Mechanical/Thermal Stability Design

For satellite imaging with large angle and frequent attitude maneuvering on orbit, changes in thermal environment will cause thermal stress and deformation of hyperspectral imager and its installation structure, which will affect optical axis pointing and geometric matching of optical system, and ultimately the imaging quality. Therefore, the design of mechanical/thermal stability is very important for on-orbit imaging quality assurance.

High-resolution hyperspectral satellites adopt high-stability mechanical/thermal structure assurance technology and high-precision active temperature control technology through payload-platform thermal integration design to ensure that the

stress release processes of the spectrometer are set up for the high stability in the mechanical/thermal environment on-orbit to eliminate the effects of internal stress.

5.5 Scheme Description of High-Resolution Interferometric Hyperspectral Imager

Spatial-temporal jointly modulated interferometric spectrometer is a newly developed interferometric imaging spectrometer, with high-energy utilization, high resolution, and SNR. The system features a large aperture optical system without slit and a lateral shearing interferometer in the interferometric optical path.

5.5.1 Analysis of System Design Constraints

The system design needs to take into account various constraints from mission level, large-scale engineering system level, and satellite overall level, and performance indicators need to be decomposed from top to bottom.

5.5.1.1 Mission-Level Constraints

Mission-level constraints mainly prescribe the top-level indicators of hyperspectral imager, such as detection band, spectral resolution, ground pixel resolution, and swath width based on the exploration mission and application requirements in combination with satellite orbit, and key imaging indicators, such as on-orbit dynamic modulation transfer function, and average SNR of spectral bands according to the application requirements through the design of satellite-ground integration.

Similar to visible light remote sensing satellite system, the influence of solar elevation angle should be considered for hyperspectral remote sensing satellite system, for which solar synchronous orbit is usually chosen as its satellite orbit. Considering the requirement of solar irradiation conditions for spring, summer, autumn, and winter application capability, the local time of descending node of the orbit usually chooses at 10:30 a.m. or 1:30 p.m., and the orbit altitude is generally within 450–800 km. According to the application requirement of a resource satellite in China, the image and interference information of the Earth's surface in the visible near-infrared 0.45–0.9 μm and shortwave infrared 0.9–2.5 μm spectral bands are required. The resolution of ground pixels in visible-near-infrared band is 10 m and the number of spectral bands is 60; the resolution of ground pixels in shortwave infrared band is 20 m, the number of spectral bands is 60 too, and the imaging swath is 10 km, which can be used for hyperspectral imaging detection of mesoscale targets. In order to ensure the imaging quality, the on-orbit dynamic MTF is generally required to be

over 0.1, the average SNR in visible-near-infrared band is better than 70, the average SNR in shortwave infrared band is better than 150, and the quantization bit is 12 bit.

5.5.1.2 Design Constraints for Large-Scale Engineering Systems

In order to ensure the accuracy of ground inversion and quantitative application of hyperspectral data, the image of hyperspectral imager on-orbit should meet the requirements of absolute radiometric calibration accuracy of better than 7% and relative radiometric calibration accuracy of better than 5%. The relative spectral calibration accuracy shall be better than 2 nm to monitor the spectral quality of hyperspectral imager on-orbit. The hyperspectral imager should receive the auxiliary data broadcasted by on-board bus, arrange the auxiliary data and hyperspectral image data uniformly, and send them to the ground application system.

The hyperspectral shortwave infrared detector should work at low temperature. For the infrared hyperspectral imager which cannot frequently turn on refrigerators on orbit due to life constraints, the refrigerator should be turned on before each imaging, and then refrigerates the focal plane of the shortwave infrared detector until the prescribed low temperature.

5.5.1.3 Satellite System Design Constraints

In order to ensure the on-orbit performance, reliability and interface match between subsystems of hyperspectral imager, the design constraints of hyperspectral imager system are put forward by satellite system as a whole.

According to the different spectral bands, hyperspectral imager is designed as two spectrometers. In order to ensure the quality of on-orbit dynamic imaging, the static transmission function of hyperspectral imager shall be better than 0.2, the SNR of visible-near-infrared spectrometer better than 70:1, and the shortwave infrared spectrometer better than 150:1.

Considering the data transmission rate, it is required to compress the hyperspectral imager data. However, unlike visible light data, hyperspectral data is sensitive to large compression and has a significant loss of SNR. Therefore, compression is typically performed at a ratio of 2.5:1.

5.5.2 System Configuration and Topology

A hyperspectral imager consists of six parts: visible spectrometer main body, infrared spectrometer main body, visible spectrometer signal processor, infrared spectrometer signal processor, spectrometer controller, and spectrometer compression encoder. The schematic diagram is shown in Fig. 5.6, in which the atlas information of the target band of the ground object is converted by the main body of the spectrometer

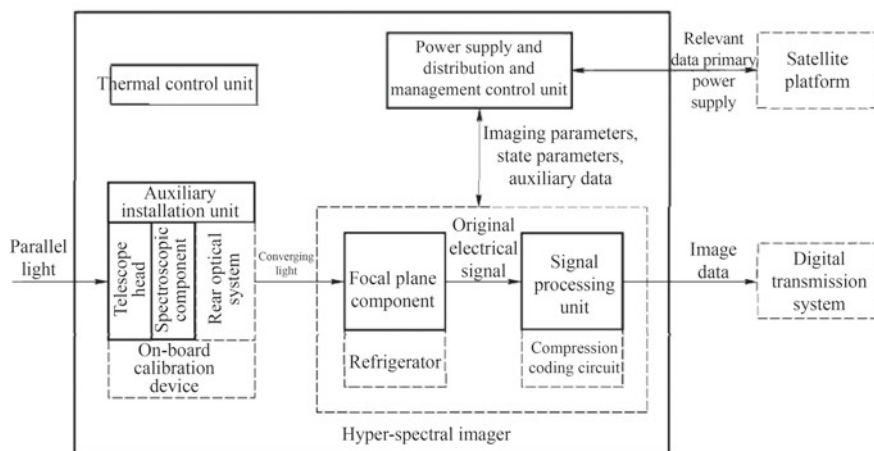


Fig. 5.6 Sketch of hyperspectral imager composition

into electrical signal; the thus obtained electrical signal is converted by the signal processing unit of the spectrometer into digital electrical signal; the obtained digital signal is compressed and encoded through the compressed encoder and output to the data transmission subsystem; the power supply and distribution control unit of the spectrometer mainly performs functions such as power supply and control.

5.5.3 Design of Working Mode

The hyperspectral imager has the following working modes: standby mode, that is, the spectral imager does not work, only the thermal control components under the control of the load thermometer are in long-term work status; the imaging mode, that is, each track of the imager can acquire visible near-infrared and shortwave infrared images on multiple boots, and the cumulative maximum imaging time of each track is not more than 15 min; on-board spectral calibration mode, which is controlled by remote control command. Spectral calibration is carried out in the shadow area of satellite to complete the calibration of spectral position accuracy and monitor the short-term changes of the system.

5.5.4 Opto-mechanical System Design

The main optical system of a typical interferometric hyperspectral imager is divided into three parts: telescope system (consisting of a prefix mirror and a collimator as

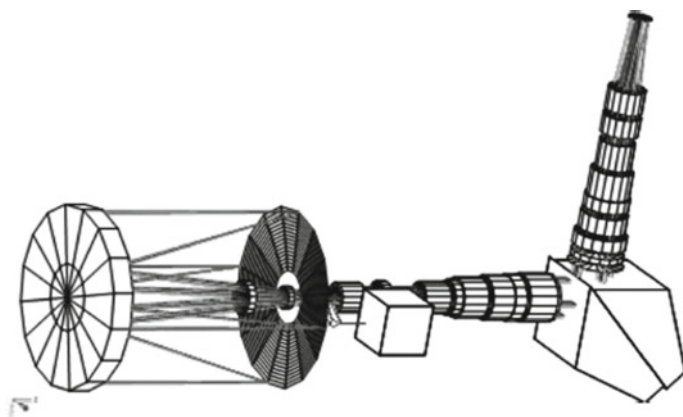


Fig. 5.7 Optical system diagram of visible spectrometer

the front subsystem of the entire optical system); interferometer (placed in a parallel optical path); Fourier mirror (the rear subsystem of the entire optical system).

5.5.4.1 Design of Optical System of Visible Light Spectrometer

In order to design a compact and light-weight system, a small solid Sagnac interferometer will be used in the visible spectrometer, as shown in Fig. 5.7. For those spectrometers whose F -number is about 6, the MTF of their optical system can generally be achieved better than 0.65.

5.5.4.2 Design of Optical System of Infrared Spectrometer

The infrared spectrometer uses a small separated Sagnac interferometer, which consists of a prefix mirror, a collimator, an interferometer, and a Fourier mirror in series. A calibration component is placed on the side of the primary image plane of the prefix mirror, as shown in Fig. 5.8.

5.5.4.3 Optical-Mechanical Structure Design

Visible spectrometer adopts the same technical principle as infrared spectrometer. Optical-mechanical system can be divided into prefix mirror module, collimator module, interferometer module, Fourier mirror module, focal and surface module, calibration module and box, etc. The main body of visible light spectrograph and infrared spectrograph are independent devices, which can perform their corresponding functions, respectively, and can also be controlled synchronously by

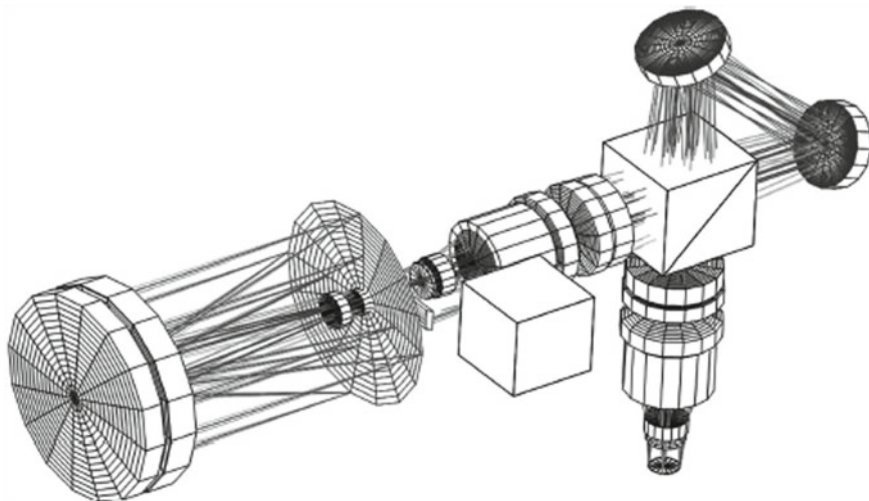
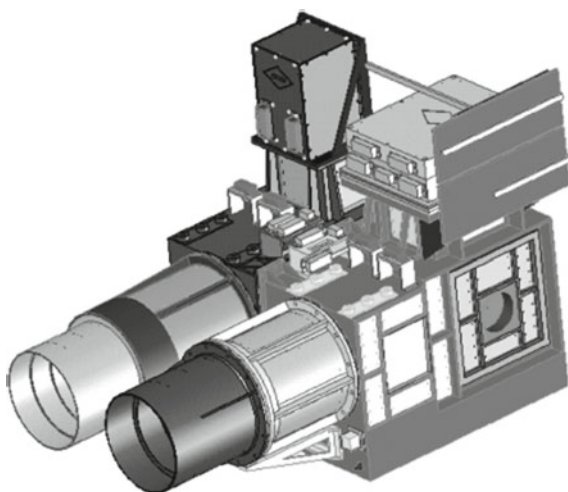


Fig. 5.8 Schematic diagram of optical system of infrared spectrometer

the controller. The two equipments are connected with each other through the box to form a hyperspectral imager assembly to meet the requirements of optical axis registration. The assembly is installed in the satellite payload compartment as a rigid whole, which is shown in Fig. 5.9.

Fig. 5.9 Appearance profile of hyperspectral imager assembly



5.5.5 *Design of Electronic System*

The electronic system of hyperspectral imager mainly includes imaging circuit of visible spectrometer (focal plane module and signal processor of visible spectrometer), imaging circuit of infrared spectrometer (focal plane module and signal processor of infrared spectrometer), optical compression encoder, and controller, etc. Its main functions include remote control and telemetry management of spectrometer, setting and control of imaging parameters (frame rate, video signal gain, etc.), distribution of primary/secondary power supply, power supply/drive/video signal processing of imaging circuit, image compression, on-board calibration control, and refrigerator control, etc.

5.5.6 *On-Board Calibration Design*

Based on the imaging characteristics of spatial-temporal jointly modulated hyperspectral imager, the position of spectral line is determined by the shear of lateral shearing interferometer and the focal length of Fourier lens. Therefore, the method of introducing a calibration light source with characteristic absorption peak at the position of primary image plane is determined to achieve on-board spectral calibration. This scheme can realize full-field calibration of system part aperture and spectral direction.

As shown in Fig. 5.10, for the on-board calibration device, the positions of two absorption peaks, λ_{N1} and λ_{H1} , are measured and restored in the laboratory as comparison benchmarks. After the launch of the satellite, the above process is repeated and the positions of the two absorption peaks, namely, λ_{N2} and λ_{H2} , are obtained. $\Delta\lambda_N = \lambda_{N2} - \lambda_{N1}$ and $\Delta\lambda_H = \lambda_{H2} - \lambda_{H1}$ are the difference between the on-board spectral position and the experimental results.

5.6 *Satellite On-Orbit Imaging Mode Design*

Unlike traditional visible remote sensing systems, hyperspectral imaging systems have many constraints on the design of imaging modes, which are often affected by energy, observation efficiency, application mode, etc. The design of imaging modes requires a trade-off among multiple factors.

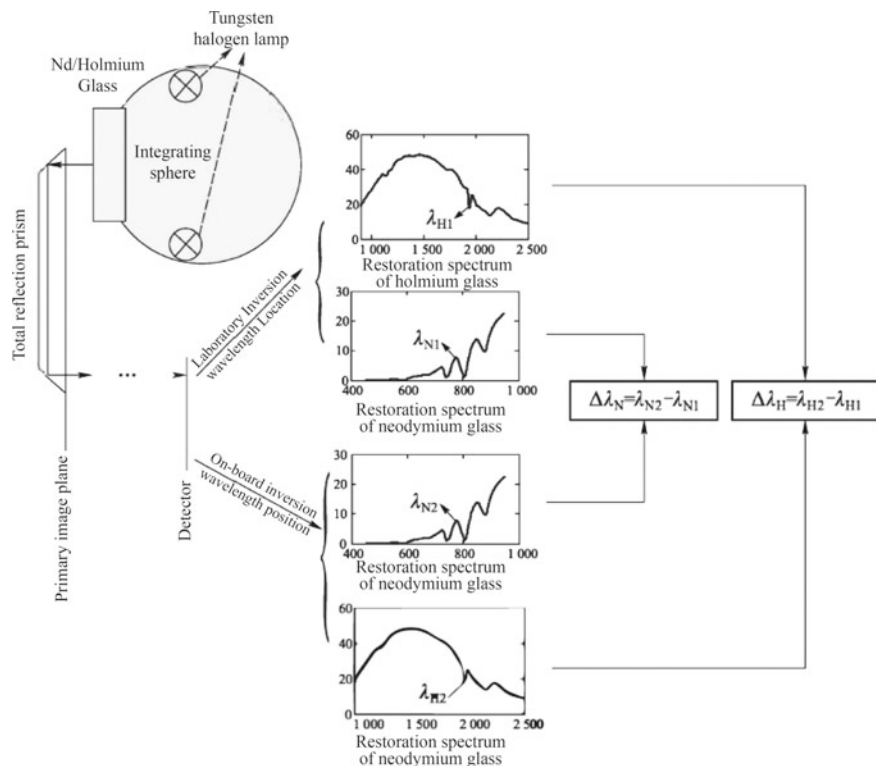


Fig. 5.10 On-board calibration diagram

5.6.1 Energy Analysis

The application demand of hyperspectral imaging system for subdivision of spectral bands and high spatial resolution highlights the problem of insufficient energy, which will directly affect the performance of hyperspectral imaging system such as SNR and MTF. To solve this problem, the whole satellite attitude “slow scanning” mode is widely used to prolong the observation time on the target. Therefore, the typical imaging mode of hyperspectral imaging system is “imaging in fly-back motion.”

5.6.2 Observation Efficiency Analysis

For disaster applications, the observation efficiency directly affects the support ability of hyperspectral imaging system for disaster relief. Therefore, satellite platform should provide whole satellite pointing fast rotation ability, which is consistent with visible light imaging system. However, for hyperspectral imaging systems with high

spatial resolution, the motion compensation of energy should be taken into account. Therefore, the agile mode of hyperspectral imaging systems is carried out under the condition of “imaging in motion,” which increases the difficulty of imaging control.

5.6.3 Application Mode Analysis

The emphasis of the application mode of hyperspectral imaging system varies with the application requirements. For example, for shallow water observation mode, hyperspectral-imaging system should consider non-along-track mode; for point targets whose spectral characteristics need to be collected, hyperspectral imaging system is required to consider acquiring multiangular hyperspectral data and multi-angularly observing targets through agile control.

5.6.4 On-Orbit Imaging Mode Design

For hyperspectral satellites that need active attitude backward-scanning imaging, multi-velocity motion compensation greatly restricts the on-orbit imaging efficiency. Considering the imaging capability of hyperspectral imager, satellite attitude maneuverability and satellite scanning compensation imaging characteristics, three types of hyperspectral imaging modes for whole satellite, i.e., single track multi-point multi-target imaging, non-along-track imaging, and same-track multiangular imaging, are designed on the premise of satisfying the requirements of on-orbit SNR, non-along-track and multiangle imaging.

5.6.4.1 Single Track Multipoint Multi-target Imaging

In this model, the fast attitude maneuverability of the satellite is utilized to image the scattered target by the fast side-sway. This mode mainly aims at the observation of multiple imaging targets in a small range along the track direction and different pointing positions in one orbit. In addition to the requirement that the satellite has better fast attitude maneuverability in the pitch direction, it is also required that the satellite can perform frequent sides way maneuvering to ensure the rapid completion of multiple target imaging missions. For sudden disaster areas, this imaging mode is most suitable for the fast observation mission.

5.6.4.2 Non-along-Track Strip Imaging

Active backward-scanning imaging mode is adopted to realize scanning and imaging of a non-along-track strip target. This model is designed to quickly acquire images of

a strip area and improve the imaging efficiency of satellites to targets such as coasts, borders, highways, and railways.

5.6.4.3 Along-Track Multiangular Imaging

The satellite adjusts the camera pointing by fast attitude maneuver, and establishes the backward-scanning velocity by combining attitude maneuver, thus realizing continuous imaging of point target or strip target at different angles. Compared with the passive along-track multiangular imaging mode, the observation angle of the satellite in the acquired image is not fixed when the camera operates in the backward-scanning model along the track.

5.7 Design and Analysis of Satellite On-Orbit Dynamic Imaging Quality

Like the visible light camera, the on-orbit dynamic imaging quality of the hyperspectral imager also includes on-orbit dynamic MTF, SNR, dynamic range, and geometric positioning accuracy. Taking the typical application of spatial-temporal jointly modulated interferometric hyperspectral imager as an example, this section focuses on the design and analysis process of on-orbit dynamic imaging quality of hyperspectral imager.

5.7.1 On-Orbit Dynamic MTF Analysis

For the MTF of on-orbit imaging system, the whole imaging link system is regarded as a linear system with spatial frequency. Although the area array detector is used in the hyperspectral imaging system, the image information acquired by both the dispersive and interferometric type hyperspectral imaging system are essentially the image information of each spatial “linear array” obtained by push-broom line by line. Therefore, for a certain spectral band, the hyperspectral image is similar to that of “single linear array CCD system.”

The environment factors affecting hyperspectral on-orbit dynamic MTF are also similar to that of visible light remote sensing system, including atmosphere, camera (optical system, optical installation, detector, and circuit), push-broom, drift angle correction error, attitude stability, frame rate setting error, flutter, stray light, and thermodynamics, etc.

5.7.1.1 Spectrometer Static MTF

In order to obtain enough energy, hyperspectral imager generally uses optical system with smaller F -number and the MTF of the optical system of more than 0.6 (full FOV). The influence factor for the processing and assembly of small aperture optical parts is about 0.85; the MTF of visible detector, the MTF of infrared detector, and the MTF of imaging processing circuit is higher than 0.4, 0.5, and 0.95, respectively. According to the static transfer function calculation formula of spectrometer, i.e., $MTF_{static} = MTF_{optical} \times MTF_{processing \text{ and } adjustment} \times MTF_{CCD} \times MTF_{electronic}$, the average of whole system static $MTF_{visible \text{ light}}$ can exceed 0.22.

In addition to the theoretical calculation of the static MTF, the static MTF of the hyperspectral imaging system is also measured in the laboratory by the fringe target test method in the development stage. The stripe target satisfying the Nyquist frequency of the detector is placed in the focal plane of the collimator, so that the parallel light emitted by the target can be imaged in the focal plane of the spectrometer detector, and each stripe is located in a row of pixels. For the test case diagram, see Fig. 5.11.

By testing the gray value DN_{max} and DN_{min} of light and dark fringes under Nyquist frequency, MTF of the image is calculated according to the following calculation formula:

$$MTF = \frac{\pi}{4} \cdot \frac{DN_{max} - DN_{min}}{DN_{max} + DN_{min} - 2DN_b} \quad (5.5)$$

where DN_b is dark current of CCD. According to the practical engineering development experience, the static MTF of hyperspectral imager with small F -Number can reach about 0.3.

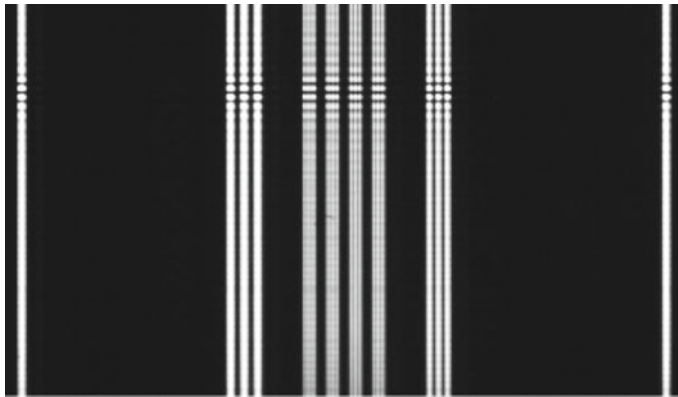


Fig. 5.11 Transfer function test stripe target map

5.7.1.2 The Influence of the Atmosphere on the System MTF

For the hyperspectral imager with a working spectral band of 0.45–2.50 μm , when the spectrometer imagines the target through the atmosphere, the reflected radiance signal of the target will be blurred by the atmosphere, which is mainly caused by the scattering and absorption of atmospheric turbulence and aerosols. This effect is caused by the uncontrollable external processes. For example, assumed that the ground target is tested at 20:1, based on the measured data on the ground and the contrast-based atmospheric transfer attenuation model, the $M_{\text{target}} \times M_{\text{atmosphere}} = 0.84$. In the satellite on-orbit imaging test, the local atmospheric conditions shall be measured quantitatively so as to give the impact of the atmosphere on MTF.

5.7.1.3 The Influence of Push-Broom on MTF

Like common linear array, CCD with area array has an inherent MTF decrease factor due to push-broom in the direction of flight. If the filling factor of the device adopted in the imager is 1, the MTF decrease factor caused by sampling at standard Nyquist frequency is

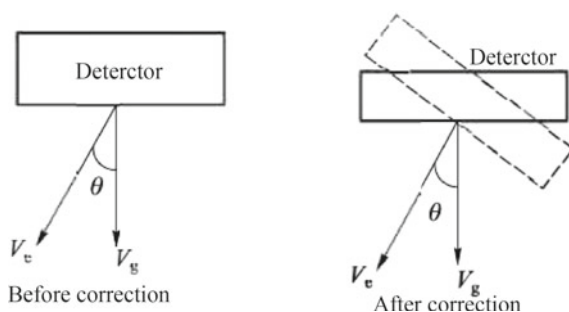
$$\begin{aligned} \text{MTF}_{\text{push-broom}} &= \sin c(\pi S v_n), \\ S &= V \cdot t_{\text{int}}, \\ V &= \frac{V_g \cdot f}{H}, \end{aligned} \quad (5.6)$$

where S is the image displacement of the target on the image plane caused by satellite motion in the integration time; v_n is the cut-off frequency ($\frac{1}{2d}$, d is the pixel size); V is the image displacement velocity; t_{int} is the integration time; V_g is the velocity of the sub-satellite point; f is the focal length; H is the orbit height of the satellite. For example, assuming that the orbital height is 500 km and focal length is 750 mm, the effect of push-broom on MTF is about 0.637.

5.7.1.4 The Effect of Drift Angle on MTF

For an interferometric hyperspectral system, the area array detector is used to obtain different spectral information of the same ground object. The effect of drift angle is similar to that on visible TDI CCD. The direction of the rolling axis of the satellite can be adjusted by the correction of drift angle to eliminate the component of the relative motion direction between the satellite and the target point on the pitch axis of the satellite on the premise that the yaw axis of the satellite is unchanged. As shown in Fig. 5.12, this results in that the normal direction of the detector coincides

Fig. 5.12 Schematic diagram of drift angle correction



with the motion direction of the ground object, ensuring that the image displacement does not affect MTF during one exposure time, and that the same ground scene does not have lateral displacement in the interference information generated in successive multiple lines, thus ensuring the quality of spectral restoration.

When the correction accuracy of drift angle is at 0.05° , the drift angle causes the transverse displacement of the image point to be 0.0008 pixels in the imaging time of a frame image for the hyperspectral imager with 180×1024 detector, which has little influence on MTF. However, in extracted interference information from continuous multi-frame interferometric images for the same ground object, the main object of LAMIS is 0.14 pixels from 180 frames of images, which is required to be eliminated by ground correction to ensure the quality of spectral restoration. It can be seen that the accuracy of drift angle correction has a great influence on the accuracy of LAMIS scene difference control and spectral restoration of 180 frame image extraction.

5.7.1.5 The Effect of Attitude Stability on MTF

Similar to TDICCD, attitude stability also has a cumulative effect on the hyperspectral interferometric hyperspectral image. In general, the working frame rate of the hyperspectral imager is much higher than the low-frequency variation of control system attitude. Therefore, according to push-broom imaging theory, the drift of low-frequency attitude can be considered as a unilateral linear motion in relatively short integration time, and the influence of linear motion on imaging quality is much slighter than that of high-frequency vibration at the same amplitude.

The influence of attitude stability on the MTF of the hyperspectral image is similar to that on the MTF of the visible camera. The difference is that visible cameras are affected by "TDI." The interferogram of interferometric hyperspectral image can be obtained by push-broom, and the cumulative effect of multiline scanning should also be considered. When the satellite attitude stability reaches $1.0 \times 10^{-3} \text{ }^\circ/\text{s}$, the relative decrease of MTF is very small, and the MTF influence factor is 0.99.

5.7.1.6 The Effect of Frame Rate Error on MTF

There are several errors that affect the accuracy of on-board frame rate data:

- (1) **The focal length determination error of the imager** $\frac{\Delta f}{f}$ of the imager must be less than 1%.
- (2) **CCD size error** $\frac{\Delta d}{d}$ (negligible);
- (3) **The error of GPS velocity-height ratio accuracy** must be less than 3%, which mainly depends on the accuracy of digital elevation map according to the accuracy analysis of velocity-height ratio calculation of GPS subsystem.
- (4) **The maximum frame rate quantization error** is 0.02 Hz after converting velocity-height ratio data into frame rate data, and 0.05% corresponding to the relative minimum frame rate of 380 Hz.
- (5) **Time delay error of data transmission path.** According to the statistics of the continuous multi-loop frame rate variation of satellite orbit simulator output, the hopping variables of the adjacent two frame rate are very slow, about 23 s. When there is a frame rate time delay of 4–5 s, the frame rate setting error of the imager is only about 0.9%.

In summary, the maximum error of on-board frame rate generation link is less than 1.5%, and the influence on the transmission function of hyperspectral imager, $MTF_{\text{frame rate}} = 0.98$.

5.7.1.7 The Effect of Whole Satellite Flutter on MTF

In the frame-frequency time of hyperspectral imager, high-frequency satellite flutter will affect the on-orbit MTF of hyperspectral imager. In general, if the flutter amplitude above the working frequency band of the spectrometer can be controlled within 0.1 pixels, the MTF will be decreased by 4.8%, which has little effect on the imaging quality. This requirement is not very difficult to implement for the spectrometer with resolution of 10 m, but it will become more difficult with the improvement of resolution.

5.7.1.8 The Effect of Stray Light on MTF

The point source signal used in the MTF test on ground is different from the surface light source on the ground object by on-orbit imaging, so that the influence of the light source outside the FOV shall be considered in the result. For example, according to the design requirements, the stray light of visible spectrometer and infrared spectrometer should not be greater than $G = 5\%$, and the MTF decrease factor should be 0.98 when the imager adopts the design of eliminating stray light.

5.7.1.9 The Effect of Thermodynamics on MTF

The optical-mechanical structure of spectrometer system is inevitably affected by the space environment when it runs on orbit, which is quite different from the ground laboratory environment. The main influencing factors are the mechanical environment in the launch segment, such as the microgravity environment, on-orbit thermal environment, and on-orbit material stress, which will cause the focal plane of the optical system to defocus, leading to a decrease in MTF. The complex condition and interaction of these factors on orbit are mainly verified by ground simulation analysis, ground mechanics, and thermal vacuum test. For hyperspectral imagery with resolution of 10 m usually but without focusing function, it's thermal/mechanical stability is very important to the imaging quality of the spectrometer. The MTF influence factor is controlled above 0.75. For spectrometers with higher spatial resolution, focusing function shall better adapt to on-orbit thermodynamic changes.

5.7.1.10 The Comprehensive Analysis of on-Orbit Dynamic MTF

On-orbit dynamic MTF of the hyperspectral remote sensing satellite system is also evaluated by MTF at Nyquist frequency. For the imaging spectrometer with the push-broom imaging system of area array or linear array, despite the spatial resolution is not high, the accuracy of satellite on-orbit drift angle control, satellite stability, and on-board flutter array still have a great impact on on-orbit imaging quality. Satellite push-broom motion and frame rate errors only cause MTF degradation along track direction, while drift angle correction errors only cause MTF degradation in the direction of vertical to orbit. Therefore, MTF along orbit and vertical to orbit should be estimated separately. The relationship between on-orbit dynamic MTF and MTF influencing factors in each step is as follows:

The system MTF in flight direction can be expressed as

$$\begin{aligned} \text{MTF}_{\text{total flight}}(\nu_n) = & \text{MTF}_{\text{target}} \times \text{MTF}_{\text{atmosphere}} \times \text{MTF}_{\text{camera}}(\nu_n) \times \text{MTF}_{\text{push-broom}} \cdot \\ & \times \text{MTF}_{\text{drift}} \times \text{MTF}_{\text{attitude stability}} \times \text{MTF}_{\text{frame rate}} \times \text{MTF}_{\text{flutter}} \\ & \times \text{MTF}_{\text{stray light}} \times \text{MTF}_{\text{thermodynamics}} \end{aligned} \quad (5.7)$$

The MTF of the system vertical to the flight direction is

$$\begin{aligned} \text{MTF}_{\text{total vertical}}(\nu_n) = & \text{MTF}_{\text{target}} \times \text{MTF}_{\text{atmosphere}} \times \text{MTF}_{\text{camera}}(\nu_n) \times \text{MTF}_{\text{drift}} \cdot \\ & \times \text{MTF}_{\text{attitude stability}} \times \text{MTF}_{\text{frame rate}} \times \text{MTF}_{\text{flutter}} \\ & \times \text{MTF}_{\text{stray light}} \times \text{MTF}_{\text{thermodynamics}} \end{aligned} \quad (5.8)$$

The on-orbit MTF statistics of satellite is as follows:

$$\text{MTF}_{\text{on-orbit}}(\nu_n) = [\text{MTF}_{\text{total flight}}(\nu_n) \times \text{MTF}_{\text{total vertical}}(\nu_n)]^{1/2}. \quad (5.9)$$

Table 5.5 Estimation results of on-orbit dynamic MTF

Estimation steps	Visible spectrometer		Infrared spectrometer	
	Flight	Vertical	Flight	Vertical
$MTF_{\text{target}} \times MTF_{\text{atmosphere}}$	0.84			
MTF_{camera}	0.28	0.28	0.35	0.35
MTF_{flight}	0.64	1.0	0.64	1.0
$MTF_{\text{attitude stability}}$	0.99			
$MTF_{\text{drift angle}}$	0.99			
MTF_{flutter}	0.96			
$MTF_{\text{stray light}}$	0.98			
$MTF_{\text{frame rate}}$	0.95			
$MTF_{\text{frame rate setting}}$	0.98			
$MTF_{\text{thermodynamic}}$	0.75	0.75	1	1
$MTF_{\text{Total flight direction}}$	0.104	0.163	0.162	0.258
MTF_{system}	0.13		0.204	

Based on the above examples, the on-orbit dynamic MTF is analyzed systematically. The analysis results are detailed in Table 5.5. It can be seen that for hyperspectral remote sensing satellites, in addition to the characteristics of the spectrometer itself, the factors such as satellite motion push-broom, thermodynamic stability, flutter, and frame rate control accuracy also have a greater impact on the on-orbit dynamic MTF of satellites, so this is the top priority of the system design of satellites. Unlike high-resolution visible light camera, because the spectrometer is without focusing function, its thermodynamic stability is very crucial to ensure that the on-orbit defocusing of the spectrometer is within the required range.

5.7.2 On-Orbit SNR Analysis

SNR mainly depends on the signal voltage of the detector and various noises introduced by the imaging circuit and the detector. Because of the particularity of spectral data of hyperspectral imager, the evaluation of on-orbit SNR, especially the average on-orbit spectral SNR, is also related to key factors such as frame sorting, image compression, and spectral restoration, as shown in Fig. 5.13.

In hyperspectral imager, visible light spectrometer and infrared spectrometer output original data contain both “graph” information and “spectrum” information. In order to improve the correlation of spectral data and reduce the impact of compression on spectral data, the spectrometer compression encoder reformats the “LASIS” images into “LAMIS” images by extracting the same target image line’s interferogram data from the consequent LASIS frames. The spatial modulation interferogram data is compressed at a certain compression ratio and transmitted through satellite

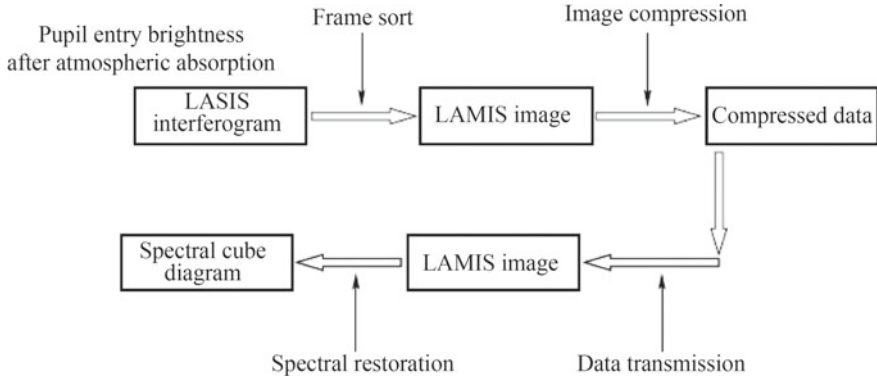


Fig. 5.13 Key factors affecting SNR of hyperspectral image data

data transmission channel. After receiving the data on the ground, the spectrum is decompressed and restored.

5.7.2.1 SNR of Interferogram

(1) Theoretical calculation

The SNR of interferogram is the ratio of intensity of signal output to that of noise output. The output signal intensity of the detector can be calculated with the average number of electrons of target signal obtained from a single pixel as follows:

$$N = \frac{\pi \cdot d^2 \cdot T_{\text{int}}}{4F^2 \cdot hc} \int_{\lambda_1}^{\lambda_2} L(\lambda) \cdot \tau_{\text{opt}}(\lambda) \cdot Q(\lambda) \cdot \lambda d\lambda. \quad (5.10)$$

For simplicity, replace the integral value with the average value:

$$N \cong \frac{\pi \cdot d^2 \cdot T_{\text{int}} \cdot \bar{L} \cdot \bar{\tau}_{\text{opt}} \cdot \bar{Q} \cdot \bar{\lambda} \cdot \Delta\lambda}{4F^2 \cdot hc}, \quad (5.11)$$

where L is the radiance of the instrument at-sensor radiance, d is the detector pixel size, T_{int} is the exposure time, τ_{opt} is the optical system transmittance, Q is the detector quantum efficiency, $\bar{\lambda}$ is the central wavelength, and F is the optical system F -number, h is the Planck constant, and c is the velocity of light.

Noise is mainly generated by detector devices and electronic circuits, including shot noise, charge transfer noise, dark current noise, readout electronic noise, and quantization noise, whose expression is as follows:

$$V_{\text{NS}} = \sqrt{V_{\text{NSH}}^2 + V_{\text{TRANS}}^2 + V_{\text{DARK}}^2 + V_{\text{ND}}^2 + V_{\text{NAD}}^2}, \quad (5.12)$$

Table 5.6 At-sensor radiance at different solar elevation angle θ and surface diffuse reflection coefficient ρ

Surface reflectance (θ, ρ)	Average at-sensor radiance of visible light/(W m ⁻² μm ⁻¹ sr ⁻¹)	Infrared average at-sensor radiance/(W m ⁻² μm ⁻¹ sr ⁻¹)
(60°, 0.6)	212.9	27.74
(30°, 0.2)	44.66	5.09
(15°, 0.05)	13.12	0.82

where V_{NSH} is shot noise, V_{TRANS} is charge transfer noise, V_{DARK} is dark current noise, V_{ND} is readout electronic noise, V_{NAD} is quantization noise.

Formula (5.10) is simplified and expressed by the equivalent number of electrons as follows:

$$\text{SNR} = \frac{N_S}{\sqrt{N_{\text{shot}}^2 + n_{\text{read}}^2}} = \frac{N_S}{\sqrt{N_S + n_{\text{read}}^2}}, \quad (5.13)$$

where N_S is the number of electrons produced by signal, N_{shot} is the number of electrons produced by shot noise, n_{read} is the number of electrons produced by detector readout noise, and the number of electrons N_{shot} produced by shot noise is the square root of the number of electrons N_S produced by signal.

The energy of hyperspectral imager optical system before radiance entry is related to solar elevation angle, ground scene reflectance, and imaging spectrum. The radiance of ground objects with different reflectivities before entering the sensor is estimated by software MODTRAN in 0.45–0.90 μm band and 0.9–2.5 μm band. The at-sensor radiance of the visible light spectrometer and the infrared spectrometer at different solar elevation angles θ and surface diffuse reflection coefficient ρ are shown in Table 5.6.

The physical meaning of the parameters of the interferogram and the design values of the scheme is shown in Table 5.7. The transmittance, central wavelength, and F -Number of the optical system are the test values of the product, and the noise-equivalent electronic count is the noise value of the device itself.

According to Eq. (5.12), the number of target signal electrons obtained by detectors at high, low, and typical test points in dynamic range can be calculated. According to Eq. (5.11) and compression effect, the SNR of interferograms at high, low, and typical test points in dynamic range can be calculated according to compression ratio, as shown in Table 5.8.

Table 5.8 shows that the SNR of the interferogram is with VNIR $\geq 77.57:1$ and SWIR $\geq 70.94:1$, when the target reflectance is 0.05 and the solar altitude angle is 15°; VNIR $\geq 339.30:1$ and SWIR $\geq 517.53:1$, when the target reflectance is 0.6 and the solar altitude angle is 60°.

Table 5.7 Calculating parameters of SNR of interferograms

Parameter	Physical meaning		Value	
			Visible light band	Shortwave infrared band
L	Instrument at-sensor radiance		N.A.	N.A.
d	Detector pixel size/ μm		16×16	30×30
T_{int}	Exposure time/MS	1.4	1.84	1.84
		0.7	0.65	0.65
τ_{opt}	Transmittance of optical system (including dimmer)		0.176	0.14
Q	Quantum efficiency of detector/%		65	60
$\bar{\lambda}$	Central wavelength/nm		675	1700
F	F-Number of optical system		5.55	4.98
h	Planck constant		6.626×10^{-34}	
c	Velocity of light/(m s^{-1})		3×10^8	
n_{read}	Noise-equivalent electrons count/ e^-		200	540

Table 5.8 Number of target signal electrons of obtained by high-, medium-, and low-end detectors and design check value of SNR of interferogram

Surface reflectance (θ, ρ)	Number of electrons/ e^-		Signal to noise ratio of interferogram			
			Visible spectrometer		Infrared spectrometer	
	Visible spectrometer	Infrared spectrometer	Before compression	After compression	Before compression	After compression
(60°, 0.60)	164,354	1,672,143	370.41	339.30	628.86	517.53
(30°, 0.20)	68,953	306,821	213.39	195.46	396.62	328.17
(15°, 0.05)	20,257	49,429	84.69	77.57	84.64	70.94

(2) Test result

In the acquired $K = 100$ interference images, the number of pixels of the interference fringes in the image except the column with zero optical path difference is selected, and the average signal intensity of the interference image of 100 pixels is calculated as the signal value, the root mean squared error of the pixel signal is calculated as noise, and the average SNR of the image is calculated by selecting the SNR of the i -row and j -column in the interference image.

(1) The average values of gray scale of each pixel S_{ij} and mean squared error σ_{ij} :

$$S_{i,j} = \frac{\sum_{i=1}^K p_{i,j,k}}{K}$$

(5.14)

$$\sigma_{i,j} = \sqrt{\frac{\sum_{i=1}^n (p_{i,j,k} - s_{i,j})^2}{k-1}} \quad (5.15)$$

(2) The SNR for each pixel $\text{SNR}_{i,j}$ is calculated as

$$\text{SNR}_{i,j} = \frac{s_{i,j}}{\sigma_{i,j}} \quad (5.16)$$

(3) The average SNR of the image SNR is calculated as

$$\text{SNR} = \frac{\sum_{i=1}^m \sum_{j=1}^n \text{SNR}_{i,j}}{m \times n} \quad (5.17)$$

where $p_{i,j,k}$ is the pixel grayscale output by the row j and column i of the k th image; K is the number of selected images; n is the number of rows of the k th image; m is the number of columns of the k th image.

In the hyperspectral imagery laboratory, 100 frames of interferogram data obtained by decompressing the data, which are downloaded by compressed encoder, are used as data sources for actual testing and calculation. The test results show that the maximum SNR of visible light spectrometer is 349.9:1, the minimum SNR is 102.9:1, the maximum SNR of infrared spectrometer is 570.9:1, and the minimum SNR is 114.2:1.

5.7.2.2 Band Average SNR

Based on the imaging mechanism of interferometric spectrum, the average SNR of the corresponding spectral band increases with the increment of the SNR of the interferogram, and the SNR of the interferogram is 2–4 times of the average SNR of the spectral band. Table 5.9 lists the average SNR of the interferogram and the spectral band under three test conditions.

Table 5.9 Laboratory test results of average SNR of visible light spectrometer interferogram and the spectral band

Testing conditions	Input radiance ($\text{W m}^{-2} \mu\text{m}^{-1} \text{sr}^{-1}$)	SNR of interferogram	Average SNR of the spectral band	Ratio
$\rho = 0.05, \theta = 15^\circ$	13.12	55	21	2.6
$\rho = 0.20, \theta = 30^\circ$	44.66	150	55.7	2.6
$\rho = 0.30, \theta = 40^\circ$	80.34	182	63	2.8

According to the ratio between the SNR of interferogram and the spectrum average SNR, the typical value of the spectrum average SNR can be estimated in the concept stage. When the hyperspectral imager is developed, it can be tested and calculated through SNR test in the laboratory. It mainly includes single-band SNR calculation and average SNR calculation.

(1) Single-band SNR calculation

After reversing 100 frames of data separately, a set of $M \times N \times I$ three-dimensional data cubes can be obtained, in which the first dimension is temporal dimension (corresponding to the along-track direction), the second dimension is spatial dimension (corresponding to the cross-track direction), and the third dimension is spectral dimension (corresponding to each spectral segment). The above data is equivalent to the monochrome images of 60 spectral bands. On each monochrome image, a small area of $M \times N$ is taken for the SNR calculation by average method/mean-variance method.

The signal of the i th spectral band:

$$S_i = \bar{L} = \frac{\sum_{m=1}^M \sum_{n=1}^N L_{m,n,i}}{M \times N} \quad (5.18)$$

The noise of the i th spectral band:

$$N_i = \sqrt{\frac{\sum_{m=1}^M \sum_{n=1}^N (L_{m,n,i} - \bar{L})^2}{M \times N - 1}} \quad (5.19)$$

The SNR of the i th spectral band:

$$\text{SNR}_i = \frac{S_i}{N_i}. \quad (5.20)$$

(2) Calculating the average SNR of spectral band

The average SNR of each working band is calculated by the following formula, thus obtaining the average SNR of imaging spectrometer.

$$\overline{\text{SNR}}_j = \frac{\sum \text{SNR}_i}{I}. \quad (5.21)$$

The average SNR of hyperspectral imager is tested and the SNR is calculated by the above testing method. The results depicted in Fig. 5.14 show that the average SNR of 5–10 band is 14.19:1, that of 11–20 band is 28.68:1, and that of visible light spectrometer is 73.1:1.

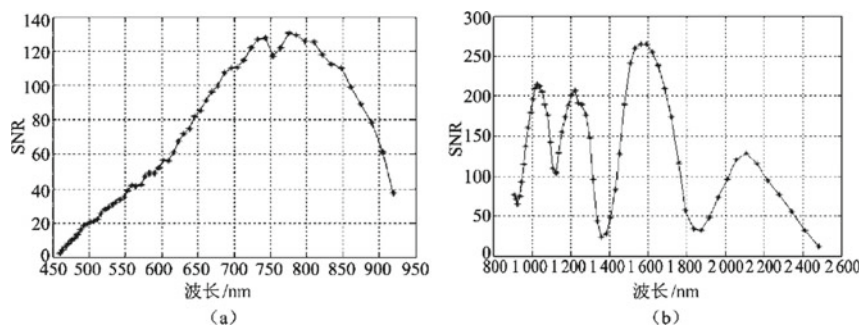


Fig. 5.14 SNR curve for each band. **a** Visible-near-infrared spectrometer; **b** shortwave Infrared Spectrometer

5.7.3 On-Orbit Dynamic Range Analysis

Dynamic range refers to the range of ground object radiance which can be effectively detected by remote sensing camera, i.e., the range of linear response to the input signal, which is expressed by the ratio of critical saturated at-sensor radiance to the at-sensor radiance equivalent to exposure of the formed noise (RMS). The dynamic range can be used to evaluate the rationality of quantization series and gain settings of remote sensing cameras.

In the laboratory, the SNR and dynamic range of the remote sensing camera can be tested by using the integrating sphere as the light source under the ground calibration test, and the response curve is fitted to calculate the linear metric. In addition, the camera's on-orbit dynamic range and linear metrics can be given through on-orbit testing.

Based on the laboratory measurement and MODTRAN software analysis results, the maximum input radiance of the ground object and the corresponding solar elevation angle and ground reflectivity conditions under different gains can be obtained for the spectrometer operating on orbit. The solar elevation angle and reflectivity characteristics of the mission target are estimated, and the spectrometer gain parameter can be adjusted to obtain a better image dynamic range response.

The observation dynamic range of the camera is calculated based on the response curve of the spectrometer system and the calculation results of MODTRAN software, as shown in Table 5.10.

The results show that the maximum observation conditions are that the solar elevation angle is not less than 60° , with ground reflectivity of 0.6.

Table 5.10 Dynamic response range of hyperspectral imager

Visible spectrometer						
<i>Maximum response</i>	<i>Gain 1</i>	<i>Gain 2</i>	<i>Gain 3</i>	<i>Gain 4</i>	<i>Gain 5</i>	<i>Gain 6</i>
DN value	2896	2846	2882	2843	2895	2873
Solar altitude angle/(°)	60	35	25	45	50	45
Surface reflectance	0.6	0.65	0.7	0.25	0.15	0.1
Incident spectral radiance/(W m ⁻² μm ⁻¹ sr ⁻¹)	212.9	144.26	108.26	76.31	55.225	38.43
<i>Minimum response</i>	<i>Gain 1</i>	<i>Gain 2</i>	<i>Gain 3</i>	<i>Gain 4</i>	<i>Gain 5</i>	<i>Gain 6</i>
DN value	307	351	464	598	792	1077
Solar altitude angle/(°)	15	15	15	15	15	15
Surface reflectance	0.05	0.05	0.05	0.05	0.05	0.05
Incident spectral radiance/(W m ⁻² μm ⁻¹ sr ⁻¹)	13.12	13.12	13.12	13.12	13.12	13.12
Infrared spectrometer						
<i>Maximum response</i>	<i>Gain 1</i>	<i>Gain 2</i>	<i>Gain 3</i>	<i>Gain 4</i>	<i>Gain 5</i>	<i>Gain 6</i>
DN value	1967	2772	2899	2887	2899	2884
Solar altitude angle/(°)	70	70	55	45	45	20
Surface reflectance	0.7	0.7	0.6	0.5	0.35	0.6
Incident spectral radiance/(W m ⁻² μm ⁻¹ sr ⁻¹)	35.5	35.5	18.4	12.925	17.775	9.41
<i>Minimum response</i>	<i>Gain 1</i>	<i>Gain 2</i>	<i>Gain 3</i>	<i>Gain 4</i>	<i>Gain 5</i>	<i>Gain 6</i>
DN value	232	241	294	327	348	383
Solar altitude angle/(°)	15	15	15	15	15	15
Surface reflectance	0.05	0.05	0.05	0.05	0.05	0.05
Incident spectral radiance/(W m ⁻² μm ⁻¹ sr ⁻¹)	0.82	0.82	0.82	0.82	0.82	0.82

5.7.4 Analysis of Geometric Positioning Accuracy

Although the hyperspectral imaging system uses the area array detector, whether it is dispersive or interferometric, the detector in its flight direction is used to “undertake” various spectral bands after the splitting. Therefore, hyperspectral imaging system is essentially “linear array” imaging in spatial dimension, which is similar to TDI CCD imaging. For details about Geometric Positioning Accuracy Analysis, see Chap. 3.

5.8 Calibration Technology of Hyperspectral Imaging System

Imaging spectrometer calibration, an important part of quantitative analysis of the hyperspectral remote sensing, is to establish the quantitative relationship between the Digital Number value (DN value) output by each detector unit of imaging spectrometer and the input radiance in its corresponding FOV. Hyperspectral imaging data can be used to extract real physical parameters of ground objects, to compare hyperspectral images acquired in different regions or at different times, and to perform joint analysis data from different sources only after calibration and correction of imaging spectrometer. According to the different calibration contents, the calibration of imaging spectrometer usually includes spectral calibration and radiometric calibration.

5.8.1 Spectral Calibration

By a spectral calibration, the spectral response function in each band of imaging spectrometer is determined, thus obtaining the central wavelength and equivalent bandwidth of each band. Spectral calibration is the basis of radiometric calibration of imaging spectrometer, and is usually performed with wavelength scanning method by a laboratory spectral calibration system, which is composition of dedicated monochromator, collimation system, and light source.

5.8.2 Radiometric Calibration

By a radiometric calibration, the response of the imaging spectrometer system on radiation can be determined for each band to provide a radiometric correction coefficient for each detection unit, i.e., the output digital number values are related to the radiance values. Each pixel in each spectral band can be radiometrically corrected according to its corresponding correction coefficient in the hyperspectral image processing to obtain the at-sensor target radiance. In addition, radiometric calibration can eliminate the image defects caused by the nonuniformity of detector response to some extent.

Radiometric calibration can be divided into relative calibration and absolute calibration according to different requirements or purposes of application. According to the different stages of development and operation of imaging spectrometer, radiometric calibration includes laboratory radiometric calibration, on-board radiometric calibration, and calibration at radiometric calibration test site.

5.8.2.1 Laboratory Radiometric Calibration

Laboratory radiometric calibration refers to the calibration of the absolute response of imaging spectrometer in the laboratory by using high precision and high-stability standard radiation source during the development process and before delivery for satellite mounting. The accuracy of laboratory radiometric calibration is the highest, and the subsequent calibration should be compared and corrected on these original data.

5.8.2.2 On-Board Radiometric Calibration

On-board radiometric calibration is also known as on-orbit radiometric calibration. Because the performance of imaging spectrometer often varies with the aging of optical and electronic components and the change of space environment, and the ground calibration equipment cannot fully simulate the space environment, the on-orbit calibration should be carried out to directly represent the current operational state of imaging spectrometer. Space-borne imaging spectrometer is equipped with on-board internal calibration system and on-board solar calibration system, by the later, the on-board imaging spectrometer is absolutely calibrated and the artificial light source in the internal calibration system can also be monitored and corrected.

5.8.2.3 Radiometric Calibration Test Site

Radiometric calibration test site refers to the calibration of the sensors through ground synchronization measurements at the selected site under normal operating conditions. Considering the influence of atmospheric transmission and environment, it can achieve absolute calibration of the sensor in full synchronization with the acquisition of ground images. Radiometric calibration test site should be scheduled periodically throughout the lifetime of the sensors for the authenticity of hyperspectral image product. When the remote sensing platform flies over the test site, several areas can be selected for the radiometric correction. At present, the commonly used calibration methods of field radiometric correction include reflectance-based method, radiance-based method, and irradiance-based method, etc.

5.9 Application of Hyperspectral Remote Sensing Satellite

5.9.1 Geological Mineral Survey

Regional geological mapping and mineral exploration are one of the main applications of hyperspectral data. Most rocks and minerals can be distinguished by spectral

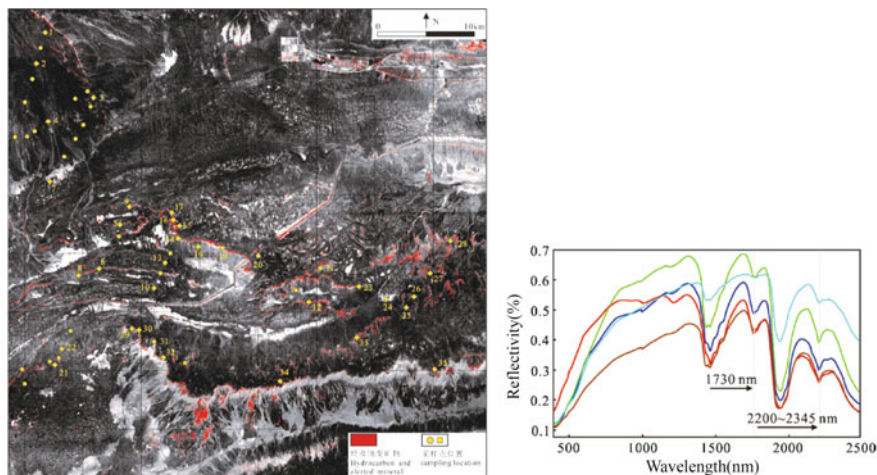


Fig. 5.15 Distribution of hydrocarbon and altered mineral information in the northeast margin of Junggar Basin (Hymap data provided by the AGRS), reprinted from Ref. [1], copyright 2019, with permission from ACTA GEOLOGICA SINICA

feature, which enables the hyperspectral remote sensing to be used for geological mapping. Different minerals and rocks can be identified by their spectral characteristics on the electromagnetic spectrum. Figure 5.15 shows the distribution of hydrocarbon and altered mineral information in the northeast margin of Junggar Basin.

5.9.2 Observation of Oil and Gas Fields

The underground oil and gas may lead to the Earth's surface under certain conditions, and some specific phenomena may appear on the Earth's surface, which will provide useful clues for hyperspectral oil and gas exploration. Figure 5.16 shows the application of oil and gas field observation.

5.9.3 Marine Application

A hyperspectral imager with the band covering 0.4–0.9 μm and a spectral resolution up to 5 nm can accurately restore spectral information to produce bathymetric charts. Hyperspectral remote sensing satellites detect bays, rivers, and other shallow water areas, serving global coastal research and environmental monitoring.

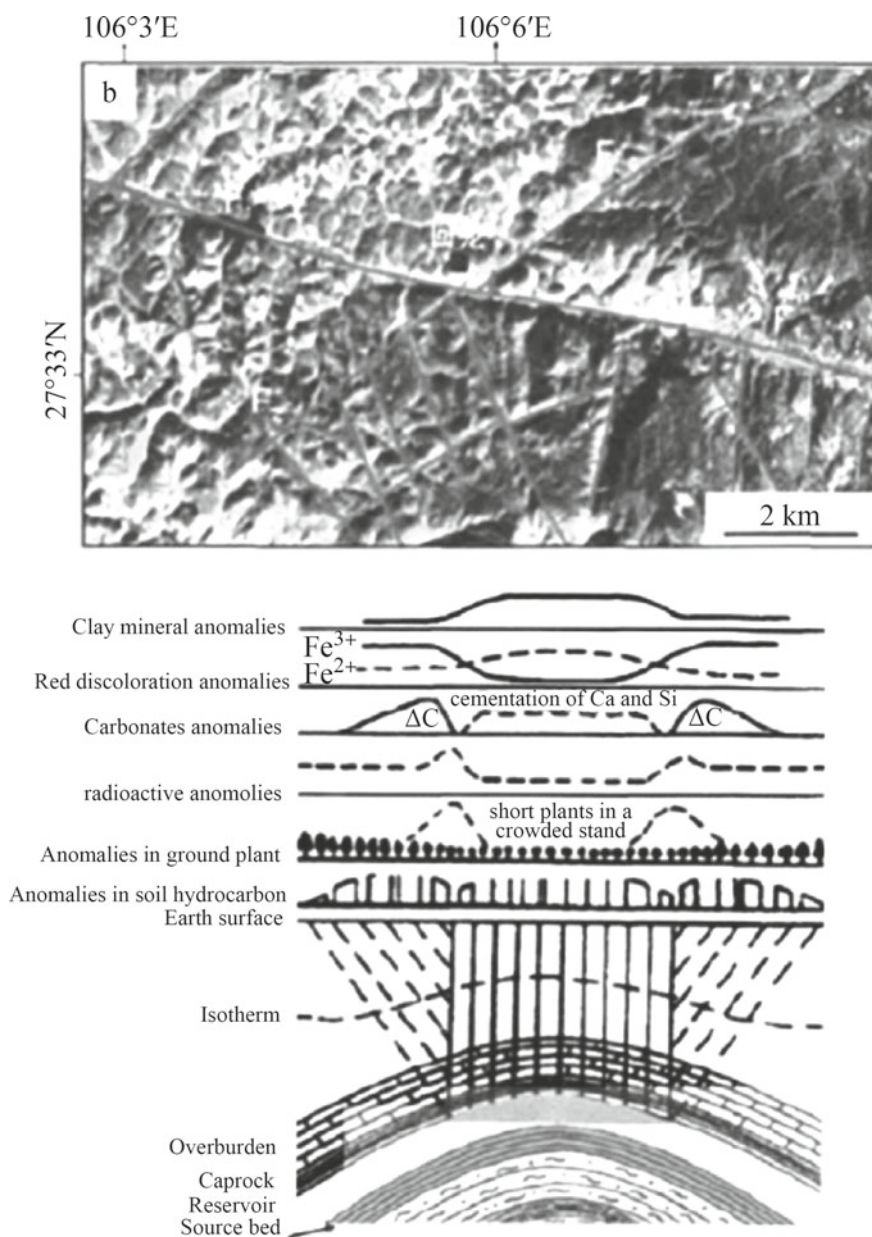


Fig. 5.16 Observation on and application of oil and gas field

5.9.4 Forestry Application

The response of vegetation to electromagnetic waves is that the spectral reflective or emissive characteristics of vegetation are determined by its chemical and architecture characteristics, which are closely related to the health and growth conditions of vegetation. The information of leaf area index and chlorophyll content can be directly reflected by full-spectral hyperspectral imaging using the spectral derivation method to eliminate soil background reflection, canopy color contamination, and atmospheric effect. The information of wetland vegetation types can be extracted from the hyperspectral data under different angles by calculating vegetation indices and image fusion.

5.9.5 Agricultural Application

Full-spectral hyperspectral remote sensing can monitor crop growth, that is, by acquiring biological, biophysical, and biochemical parameters such as chlorophyll concentration, chlorophyll density, leaf area index, biomass, nitrogen content, light, and effective absorption coefficient of plants, so as to effectively monitor crop growth and predict yield. Figure 5.17 gives an example of the application of hyperspectral in crops classification.

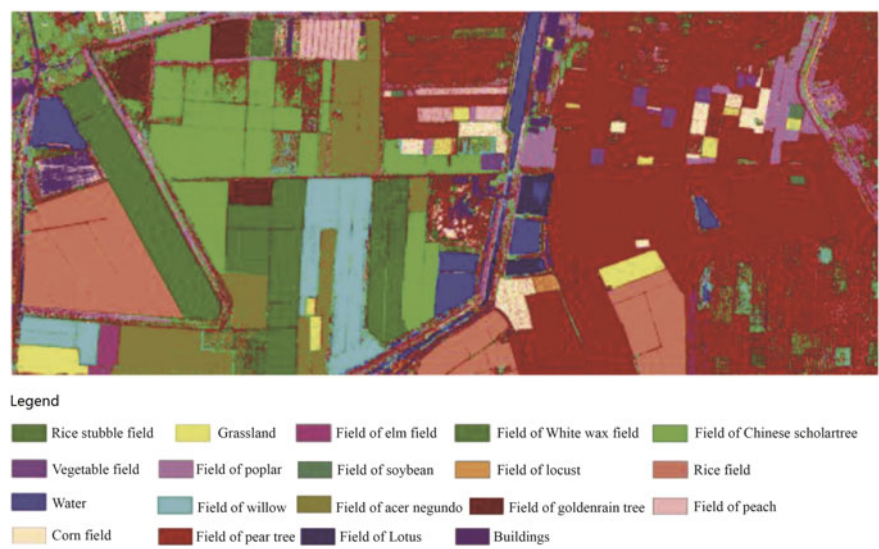


Fig. 5.17 Land cover classification map of Matiwan Village using aerial hyperspectral remote sensing data, reprinted from Ref. [2], copyright 2016, with permission from Journal of Remote Sensing

5.9.6 *Monitoring of Water Pollutants*

Hyperspectral remote sensing can effectively monitor coastal and terrestrial water quality by capturing the complex and changeable optical characteristics of coastal and terrestrial water, and improve the accuracy of water quality monitoring. The content of suspended substances in water is one of the important water quality parameters.

5.10 Summary

At present, the space-borne hyperspectral imager will enter a new era, but the space-borne hyperspectral imager system is still mainly used as a general instrument for various user applications due to the complexity of technology and high cost. In order to meet the special requirements of various users, there are many constraints on instrument design, which restricts the industrial application of space-borne hyperspectral imaging technology to a certain extent. The subdivision of application field may promote the development and popularization of hyperspectral imaging technology. In the civilian field, hyperspectral imagers mainly meet the requirements of geosciences by expanding its swath and improving its sensitivity. Military hyperspectral imagery will be further developed in terms of spatial resolution, spectral coverage, and real-time information processing capabilities.

Research on core spectroscopic devices, large-scale high-frame rate focal planes, calibration, information processing, and inversion technologies related to space-borne hyperspectral imaging technology is being vigorously promoted to meet the needs of national economic construction, social development, and national defense security.

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Chapter 6

Design and Analysis of High-Precision Stereo Surveying and Mapping Satellite System



6.1 Overview

Combining with the development and application of China's high-precision stereo surveying and mapping satellite system, this chapter focuses on the technical characteristics of high-precision stereo surveying and mapping satellite, the overall design method for high-precision stereo surveying and mapping requirements, including system design elements, accuracy and stability analysis of internal and external orientation elements, and high-precision geometry calibration, photogrammetric adjustment and application technology.

6.1.1 Development Overview

From 1987 to 2005, China successfully launched and recovered seven film-based photogrammetric positioning satellites. Recoverable satellites are difficult to obtain continuous images of ground targets on orbit because of their short on-orbit operation time and weather effects.

In 2004, a small satellite Exploration No. 1 with three-line array for stereo surveying and mapping function was launched, on which a three-line array Stereo Surveying and Mapping Camera (SSMC) was installed, with a ground pixel resolution of 10 m. Since 2010, China has launched satellites Tianhui-1 and ZY-3 with the three-line array stereo surveying and mapping technology system, with a surveying and mapping capability of 1:50,000. Many optical surveying and mapping satellites have been launched worldwide, and the main technical indicators are shown in Table 6.1.

Table 6.1 Some advanced optical surveying and mapping satellites

Satellite	Country	Surveying and mapping methods	Orbit altitude (km)	Resolution (m)	Uncontrolled positioning accuracy (m)
SPOT-5	France	Dual-line-array	832	2.5	Plane 50, elevation 6
ALOS-1	Japan	Three-line array	691.65	2.5	Plane 25, elevation 5
Cartosat	India	Double linear-array	618	2.5	Plane 25, elevation 5
ALOS-3	Japan	Double linear-array	618	0.8	—
ZY-3	China	Three-line array	506	2.5/4	Plane 10, elevation 5

6.1.2 Trend of Development

The surveying and mapping satellite represented by SPOT-5, ALOS, and Cartosat is a special sort of satellite. Several cameras with strict angle relations are deployed along the orbit direction to achieve stereoscopic observation on the target. The resolution of ground pixels of satellites already in service on orbit is mostly between 2 and 5 m. At present, dual-linear array stereo surveying and mapping satellite with 1 m resolution is being developed.

6.2 Requirement Analysis

Since 1990s, 3S technology represented by Geographic Information System (GIS), Remote Sensing (RS), and Satellite Navigation and Positioning (GPS) has developed unprecedentedly, and has penetrated into all aspects of the national economy, thus forming and promoting the rapid development of geospatial information industry. With the development of China’s surveying and mapping satellite technology, this technology will further promote the development of China’s geographic information industry by China’s geospatial data production, processing services, and other industrial chains. High-resolution stereo satellite images with considerable commercial value can not only directly produce 4D surveying and mapping products or obtain higher value-added thematic products through deep processing, but also be used in land and resources, transportation, water conservancy, railway, civil affairs, agriculture, forestry, environmental protection, public emergency, etc. The related products can also be combined with automobile, mobile phone, and other navigation terminals to extend applications and services to all aspects, such as the social public clothing, food, housing, and transportation.

6.3 Key Performance Index and Connotation of Optical Surveying and Mapping System

The core product of optical surveying and mapping is the surveying and mapping product. The magnitude of the map scale determines the accuracy of the map and the carrying capacity of the geographic information on the map. Topographic map information mainly includes content, plane position, and elevation. The content of a map is a variety of natural and artificial elements represented on the map, which mainly depends on the resolution of the image and the observation spectrum. The planar position of the ground objects elements in the absolute coordinate system depends on the internal and external orientation elements of the imaging system. The elevation is used to describe the fluctuation of terrain, which is determined by measuring the parallax of image points of stereo image pairs. It depends on the selection of the base-to-height ratio of the imaging system, the internal and external orientation elements and the Ground Control Point (GCP).

Like other remote sensing satellites, image quality and resolution are very important, which are not discussed here. In addition, the core indicators of the surveying and mapping satellite are the base-to-height ratio (H/B) and the accuracy of ground position, both of which are also the key to evaluate the satellite surveying and mapping system.

6.3.1 H/B

In stereographic surveying and mapping processing, the ideal relative elevation accuracy σ_h depends on the surveying and mapping scale M_p , the H/B , and the image coordinate measurement accuracy σ_m :

$$\sigma_h = \sqrt{2} M_p \frac{H}{B} \sigma_m, \quad (6.1)$$

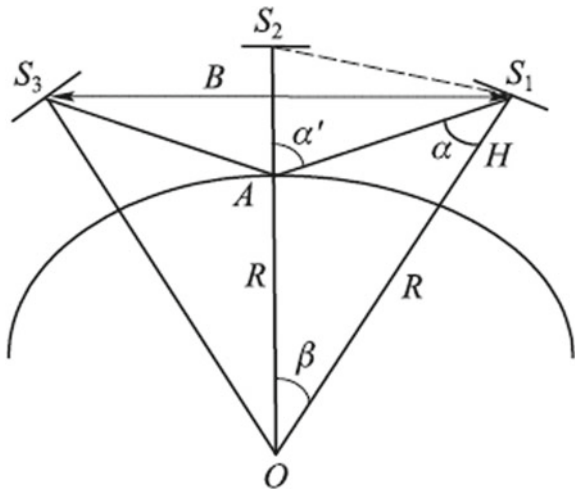
where B is photographic baseline, H represents flight height.

B/H is the ratio of photographic baseline to flight height, which is called H/B . It can be seen that it is beneficial to improve the elevation accuracy when H/B is greater than 1. If H/B is too large, the projection difference will be increased, which will cause image distortion and affect the matching (measurement) accuracy. German scholars have obtained the following conclusions through a large number of DEM point matching experiments, that is, when H/B is 0.8–0.9, the processing precision is the best. Baseline B has a triangular geometry, as shown in Fig. 6.1.

The equation for calculating H/B considering the curvature of Earth is as follows:

$$B/H = 2 \times \frac{1}{\tan \frac{\beta}{2} + \arctan(\alpha + \beta)}. \quad (6.2)$$

Fig. 6.1 Baseline diagram



In order to ensure that the H/B is within the optimal range of 0.8–0.9, the satellite orbit altitude and baseline length should be considered comprehensively. The length of the baseline is directly related to the intersection angle α of the three-line array camera, as shown in Fig. 6.2.

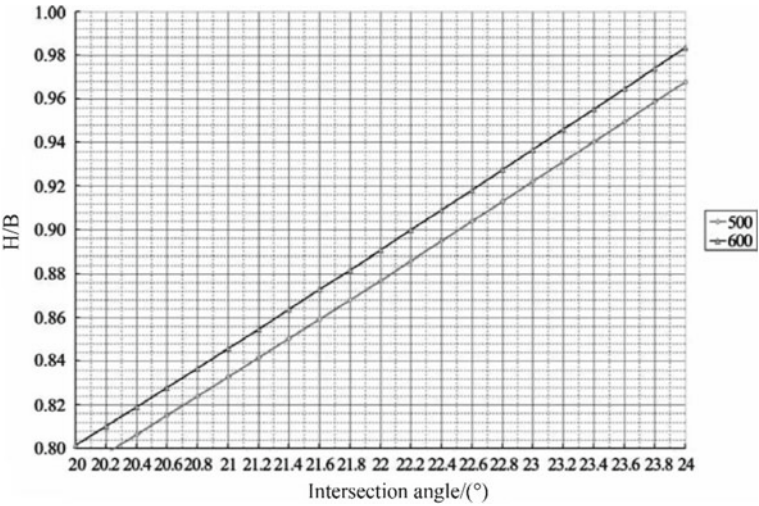


Fig. 6.2 Relationship curve of the inclusion angle between the H/B and the camera angle at different orbit altitudes

6.3.2 Ground Geometric Positioning Accuracy

Geometric positioning accuracy is the core index of high-precision surveying and mapping satellite, and is also the key to the overall design of surveying and mapping satellite. This index is a satellite-ground integration index, which uses the high-precision orbit data and attitude data on the satellite in combination with the Earth model to carry out systematic geometric correction of the image, to eliminate various systematic errors caused by the satellite push-broom imaging motion, and to finally determine the root mean square error of the target position on the map. The positioning accuracy of the surveying and mapping image is evaluated after interior and exterior orientation elements are corrected and the system errors are removed, which mainly includes the evaluation of the absolute positioning accuracy and relative positioning accuracy. The analysis of the factors affecting positioning accuracy is shown in Fig. 6.3.

Surveying and mapping satellites usually adopt multiline array stereo imaging system. The integrated design of multi-linear array camera and multi-star sensor is used to improve the attitude measurement accuracy, stability and data correlation of forward-view, nadir-and backward-view imaging process. The stability of H/B is also improved through the ground multi-star sensor. The angle element attitude

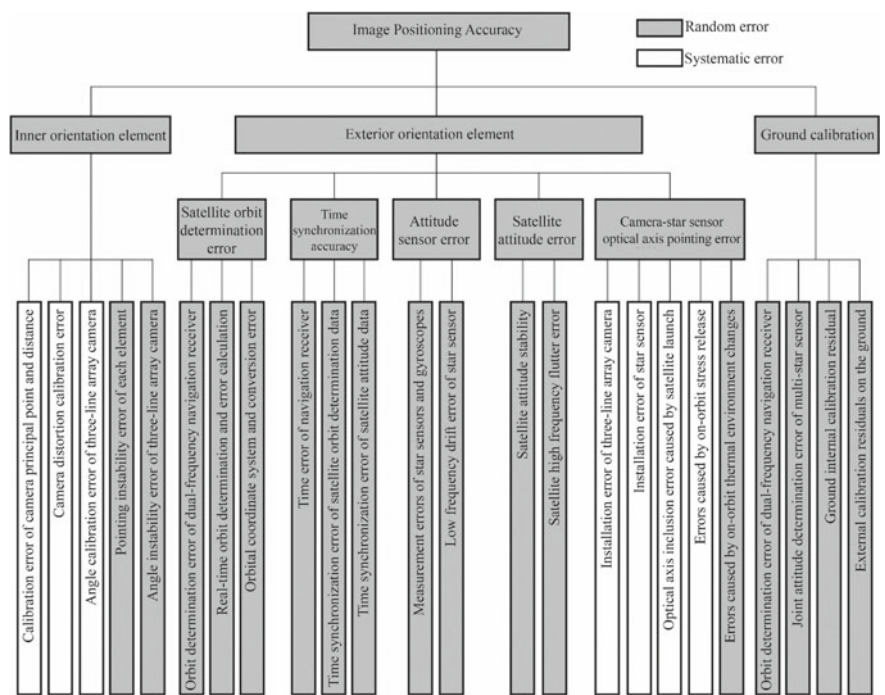


Fig. 6.3 Analysis of factors affecting positioning accuracy

measurement error can be reduced by joint attitude determination. In addition, dual-frequency navigation receiver is adopted to further improve the accuracy of satellite orbit determination through ground processing, so as to enhance the positioning accuracy of the surveying and mapping satellite system.

For three-line-array stereo surveying and mapping satellite, the main error sources of relative positioning accuracy include the instability error of camera positioning elements, the angle instability error of the three-line array camera, the attitude stability and high-frequency flutter in satellite push-broom imaging, and the residual error in the ground calibration. The absolute positioning accuracy is affected by both internal and external positioning elements, and the influence factors are more complicated. Besides the influence factors of relative positioning accuracy, the influence factors such as orbit determination error, time synchronization accuracy, attitude sensor measurement error, satellite attitude determination error, thermal instability error between camera and star sensor optical axis, and residual calibration error of ground external calibration are also included.

6.4 Analysis of Satellite Surveying and Mapping System

Satellite surveying and mapping is to obtain global geographic information by means of photographic observation on Earth by satellite in different angles, and the surveying and mapping products such as digital topographic maps, digital elevation maps, and orthophoto maps of different scales on the ground are obtained after precise processing on the ground. At present, the transmission type photography surveying and mapping system mainly includes three types: single-line-array, dual-line-array, and three-line-array.

- (1) Single-line-array surveying and mapping system: by adjusting satellite attitude and changing the optical axis direction of the camera, overlapping images of the same object and different observation directions can be obtained from same orbit or different orbits to form a stereo image.
- (2) Dual-line-array surveying and mapping system: two-line array cameras are installed on the satellite at a certain angle, and overlapping images of the same object are obtained from two different observation directions in one orbital period to form stereo images.
- (3) Three-line array surveying and mapping system: three-line array cameras are installed on the satellite at certain angles, and overlapping images of the same object are obtained from three different observation directions in one orbital period to form a stereo image.

As shown in Table 6.2, stereo surveying and mapping of the same area shall be realized through attitude maneuver by single-line-array surveying and mapping system, which is flexible in use, but difficult to achieve large-scale surveying and mapping with its low surveying and mapping efficiency. For dual-line-array surveying and mapping satellite, overlapping images on the ground can be acquired through

Table 6.2 Optical surveying and mapping system

Surveying and mapping system		Advantage	Disadvantage
Single-line-array surveying and mapping system		Only a camera can accomplish the task of stereo surveying and mapping through the rapid satellite attitude maneuver. The design of satellite is relatively simple	High requirements on fast stability and pointing ability of satellite after rapid attitude maneuver. Restricted by satellite speed and observation angle, the area of overlapping image acquired at one time is small, and the efficiency of surveying and mapping is not high
Dual-linear array surveying and mapping system		Overlapping images on the ground can be acquired through continuous observation, which has high efficiency in surveying and mapping	Two cameras are required to be installed on the satellite at the same time. The whole satellite is large in size
Three-line-array surveying and mapping system		Increasing observation quantity to the dual-line-array can further reduce the requirement for satellite exterior orientation elements. Satellite can continuously observe and acquire overlapping images on the ground, which has high efficiency in surveying and mapping	Through three cameras to achieve stereo surveying and mapping mission, the satellite size is larger

continuous observation with high surveying and mapping efficiency. Moreover, the angle between cameras can maintain high stability on-orbit because the two cameras are installed on the same basis, which is conducive to the realization of high positioning accuracy. Compared with dual-line-array surveying and mapping system, the accuracy requirement of external orientation elements is reduced by increasing observation quantity in the three-line-array surveying and mapping system, but three cameras will cause the size of the whole satellite too large.

For the dual-linear array surveying and mapping system, multi-beam laser altimeter can be configured against its shortcoming of less observation for acquiring the range information of some objects synchronously during the imaging period and participating in image adjustment processing in the ground processing, so as to improve the accuracy of image elevation positioning.

6.5 Inner Orientation Element Requirements and Stability

6.5.1 Requirements on Inner Orientation Element

For the stereo surveying and mapping camera, both imaging quality and the stability of the inner orientation elements must ensure that the internal geometric accuracy of the camera is consistent. The inner orientation elements of the stereo surveying and mapping camera system can be obtained by ground testing. In the ground test, high-precision test calibration of the camera's principal point, principal distance, and distortion must meet the user's requirements on stereo image positioning accuracy. For 1:50,000 scale surveying and mapping satellite, the measurement accuracy of the inner orientation elements requires that the calibration accuracy of principal distance is better than 20 μm , the calibration accuracy of principal point is better than 5 μm , and the calibration accuracy of camera distortion is higher than 0.3 pixels.

6.5.2 Inner Orientation Element Stability

According to the needs of surveying and mapping application, the inner orientation elements in the camera on-orbit must be calibrated several times a year, so that the stability of the inner orientation elements in the camera in the period between adjacent two calibrations must meet the requirement of surveying and mapping accuracy. For the stability of the inner orientation elements in the camera in the period between adjacent two calibrations, the drift of the calibrated focal plane should not exceed the half-focal depth of the system when the ambient temperature fluctuates, otherwise the position of the focal plane of the system must be adjusted again, and the camera after focusing must be manually recalibrated on the ground; in addition, the image

height drift of the edge FOV does not exceed $2\text{ }\mu\text{m}$, otherwise the geometric accuracy of the surveying and mapping image will be adversely affected.

6.6 Measurement and Stability of External Orientation Elements

6.6.1 High-Precision Positioning Measurement

The position of satellite (camera station) is the reference of space geometric coordinates and time coordinates for surveying and mapping satellites to complete their tasks, and its positioning is one of the important links in the measurement of exterior orientation elements. In order to meet the needs of large-scale surveying and mapping, the accuracy of satellite orbit position determination must reach 10 cm level. At present, Precise Orbit Determination (POD) based on dual-frequency GPS is usually used as the primary means of positioning measurement. The GPS navigation signal is measured by dual-frequency GPS receiver, and the measured raw data is sent to the ground for orbit determination post-processing. In order to improve the accuracy of orbit determination, the original measurement data are processed and the residual errors are corrected by using the method of combining geometric with dynamic orbit determination.

6.6.1.1 Dual-Frequency GPS Navigation Signal Measurement Technology Based on Z-Tracking Technique

For high-precision surveying and mapping satellites with the high requirement on image positioning accuracy, the position of satellite must be accurately determined by imaging. By receiving dual-frequency GPS navigation signals, measuring pseudo-range and carrier phase in L1 and L2 bands is an important way to achieve precise orbit determination of satellites. To overcome the limitation of GPS services, GPS receiver manufacturers and satellite geodesists have developed a variety of methods to obtain P-code pseudo-range. Among them, Z-tracking technique is one of the commonly used methods for space-borne dual-frequency GPS receivers.

Space-borne dual-frequency GPS receiver not only tracks navigation signal, but also tracks and locks high-dynamic navigation satellite signal. As the carrier of dual-frequency GPS receiver, the satellite travels very fast (up to km/s) in space. The generated Doppler frequency shift of the signal is nearly 100 kHz, which determines that the space-borne dual-frequency GPS receiver must have the tracking and locking function of the high-dynamic navigation satellite signal to ensure that the receiver can continuously track the signal of the navigation satellite.

Dual-frequency GPS receiver operates at changeable working environment temperature under the direct interference of strong space radiation when working

in space. These factors will have a serious impact on the normal operation of the receivers, so they must be avoided and overcome as far as possible in the development of dual-frequency GPS receivers on satellites. For different attitude of satellite on orbit, multiple GPS receiving antennas with different pointing are sometimes installed on space-borne dual-frequency GPS receivers to receive enough GPS satellite signals, for which more receiving channels are required.

6.6.1.2 Post-POD Processing Technology

Space-borne dual-frequency GPS receivers download the pseudo-range and load phase of L1 and L2 dual-frequency signals measured in real time to the ground for post-POD in the ground station. The theoretical basis of POD is the satellite orbit dynamics theory, by which the geometric information provided by the real-time observations in satellite trajectories is used as the initial orbit, and then the geometric observation information and dynamic information are fused to obtain the satellite precise orbit. At present, the main methods of orbit determination include geometric-, dynamic-, and simplified-dynamic-method.

Geometric orbit determination is to determine the position of a point by directly using GPS observations, without any prior force model involved. Generally, the satellite orbit is determined by the ionosphere-free combined precise point positioning observations of GPS satellites with high-precision orbit and clock difference parameters.

Dynamic orbit determination is based on arcs rather than points. According to the dynamic model of the satellite, the satellite state parameters at the subsequent observation moments are reduced to the initial position by integrating its motion equation, and the satellite state at the initial time is determined by multiple observations. The dynamic orbit determination method is limited by the errors of satellite dynamic model, such as the error of Earth gravitational model and atmospheric damping model. Therefore, the dynamic model error can be absorbed by adding empirical force model and adjusting the parameters of dynamic model frequently, and the potential coefficient of gravity field can be estimated to achieve pure dynamic orbit determination.

The simplified dynamic orbit determination method makes full use of the geometric and dynamic information of the satellite. By estimating the random process noise of the acceleration of the carrier (generally the first-order Gauss-Markov process model), the dynamic information is weighted relative to the geometric information, and the process parameters are used to absorb the error of the satellite dynamic model. In other words, the effect of observation in the solution is increased by increasing the variance of the dynamic model noise. At present, the simplified dynamic method is used in the precise orbit determination system in business operation.

The main factors affecting POD include the measurement errors caused by on-board equipment, the errors caused by signal propagation media (including troposphere, ionosphere, receiver clock error, receiver antenna phase error, etc.), and the

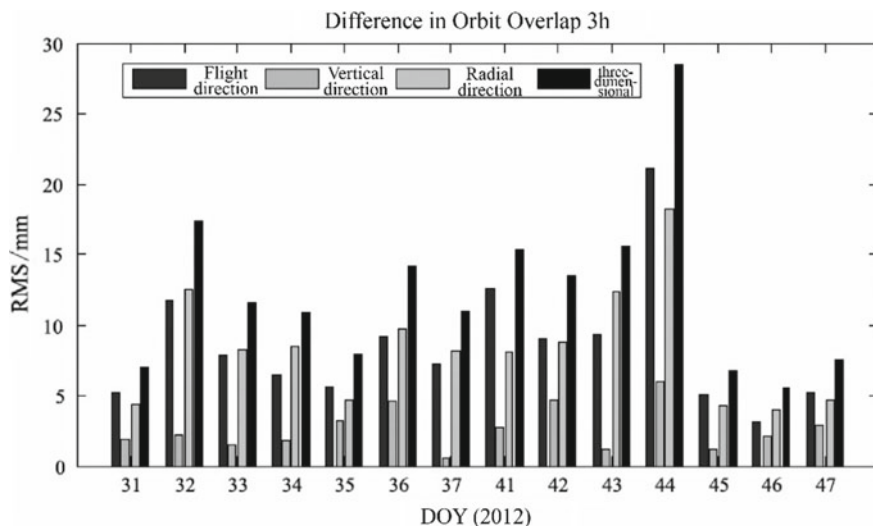


Fig. 6.4 Satellite POD accuracy (with overlapping arc method)

negative effects of satellite dynamics mathematical model on the accuracy of orbit determination (including the Earth gravitational field model, solar radiation pressure, Earth radiation pressure, atmospheric damping, solid tide, ocean tide, relativistic effect, etc.) and the accuracy of the orbit determination algorithm.

According to the accuracy analysis of on-orbit measurement data carried out by the China National Satellite Surveying and Mapping Application Center, the results show that the accuracy of three-axis orbit determination obtained by adopting overlapping arc method (i.e., using overlapping two-segment orbit determination data to compare with each other) reaches 3–5 cm; the distance measurement data of laser angular reflector and GPS orbit determination results are used to verify the residual error, and the residual is better than 4 cm. For details, see Figs. 6.4 and 6.5.

6.6.2 High-Precision Optical Axis Pointing Measurement

With the continuous development of remote sensing satellite functions and the improvement of performance indicators, the new generation high-performance optical remote sensing satellites put forward higher requirements on the accuracy of image geometric positioning. Image geometric positioning is the process of determining the geometric position information of the target in the Earth coordinate system (such as WGS84 coordinate system) from the acquired image. Therefore, the precise pointing angle of the camera optical axis shall be determined in the WGS84 coordinate system in the process of image positioning. However, the optical axis of the camera can only be indirectly measured by attitude measurement sensors such as

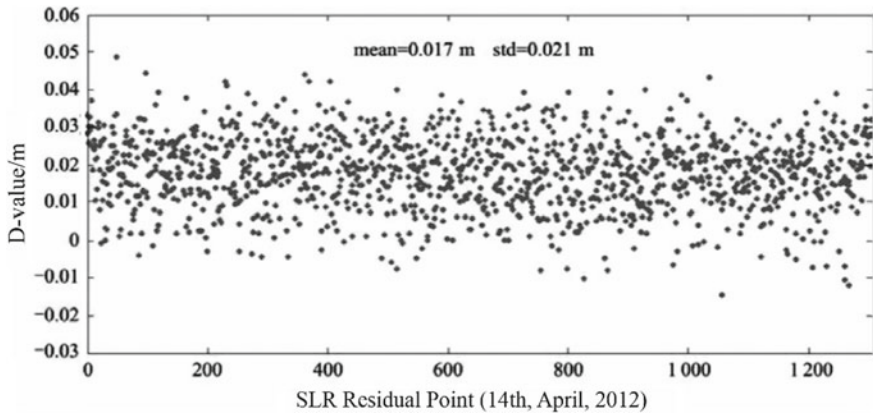


Fig. 6.5 Residuals of satellite POD results and space-borne laser corner reflector ranging results

star sensor and gyroscope instead of direct measurement on orbit. In addition, the high-precision optical axis measurement of the camera should be achieved by the high-stability control of the whole satellite and the integrated installation of sensors and cameras.

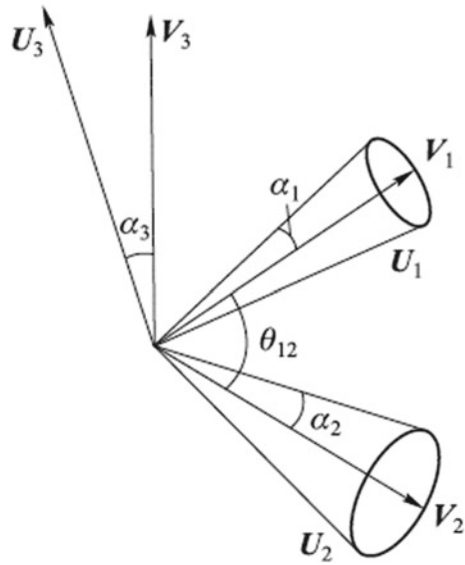
6.6.2.1 High-Precision Star Sensor Technology

Star sensor is an important measurement element of satellite attitude. Compared with gyroscope, its measurement error does not accumulate with time. It is the key to realize long-term and high-precision measurement of whole satellite attitude and camera optical axis. Because of the characteristics of star sensor itself, high optical axis measurement accuracy and poor transverse axis measurement accuracy, the high-precision measurement of inertial three-axis attitude can be achieved by the dual-star-sensor attitude determination method.

Based on the known error of the double vector, the error of the attitude determination is analyzed according to the principle of two-vector attitude determination. Let the theoretical optical axis of star sensor 1 and 2 be V_1 and V_2 (that is, V_1 and V_2 are reference vectors), respectively, the actual optical axis of star sensor 1 and 2 is U_1 and U_2 (i.e., U_1 and U_2 are observation vectors), respectively, and V_3 is perpendicular to V_1 and V_2 , U_3 is perpendicular to U_1 and U_2 . α_1 and α_2 are the optical axis measurement errors of star sensor 1 and 2, respectively, and α_3 is the coordinate axis error obtained by cross-product of double vector. The angle between the two star sensors is θ_{12} . The schematic diagram is shown in Fig. 6.6.

As mentioned above, taking the non-orthogonal coordinate system composed of U_1 , U_2 , and U_3 and the non-orthogonal coordinate system composed of V_1 , V_2 , and V_3 as the measurement coordinate system and the reference coordinate system, respectively, the error between two coordinate systems is the attitude determination

Fig. 6.6 Schematic diagram of accuracy analysis of double vector attitude determination



error caused by the star sensor measurement error. The relative transition between the two coordinate systems is represented by the angle Φ around the Euler axis. In case that the star sensor error is small, the measurement error of the double star sensor system is as follows:

$$\Phi^2 = \frac{1}{2}(\alpha_1^2 + \alpha_2^2)(1 + \csc^2 \theta_{12}) \quad (6.3)$$

It can be seen from the above equation that the determination error is minimum when the two reference vectors are orthogonal (i.e., $\theta_{12} = 90^\circ$); the smaller the angle between the two reference vectors is, the larger the attitude determination error will be. In the design of satellites, it is necessary not only to select star sensor with high precision, but also to ensure that the optical axes of star sensors are perpendicular to each other by installation.

Satellite shall use high-precision star sensor to achieve accurate attitude measurement. The fluctuation of the angle between the optical axes of the two satellite sensors on orbit is statistically analyzed. It can be seen from Fig. 6.7 that the fluctuation of the angle between the optical axes of star sensors in different periods is basically below 15° , that is, the arc-second attitude measurement is realized by single-star sensor on orbit, which is an important guarantee for the realization of high-precision geometric positioning of satellites.

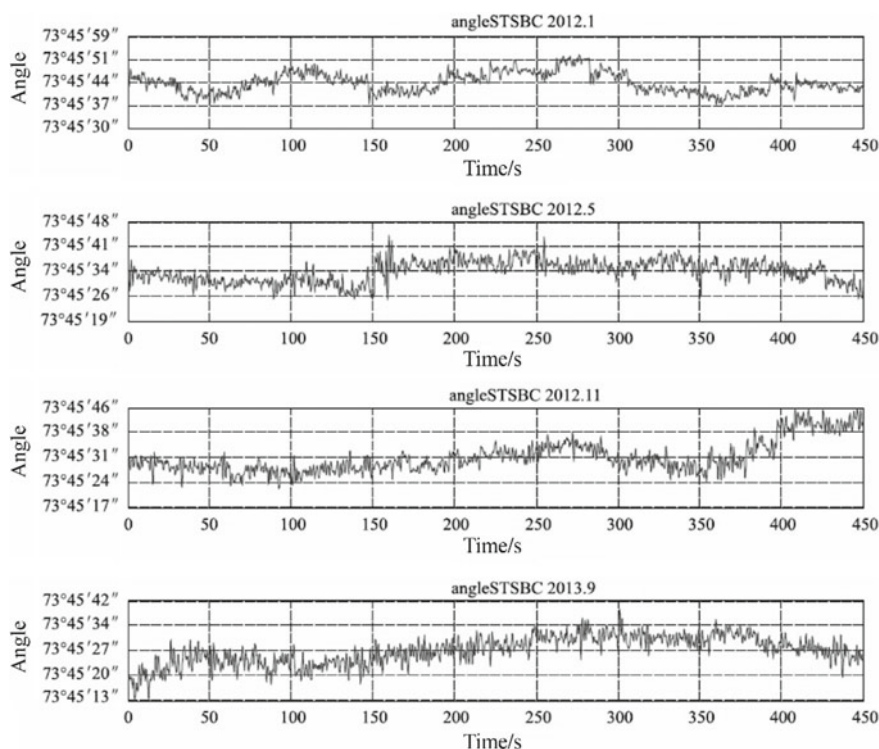


Fig. 6.7 Angle variation between optical axes of two star sensors

6.6.2.2 Joint Attitude Determination Technology of Star Sensor and Gyroscope

The attitude measurement system composed of star sensors and gyroscopes is a typical system for high-precision attitude determination for three-axis stabilized satellites. Considering high short-term accuracy of gyroscope, lack of absolute reference, and large short-period error term of star sensor due to the change of FOV and the thermal deformation, the accuracy of the output data will vary in a short period of time in attitude determination, so the two data are fused by the optimal estimation method in the current algorithm. The estimation of gyroscope drift is accomplished by measuring the value of star sensor. On this basis, the relative attitude information given by the corrected gyro measurement values over a period of time is used to complete the high-precision attitude calculation.

If the data measured by the star sensor and the gyro are transmitted into the ground station, the data can be processed by filtering technique in the ground station. The attitude is calculated by using the corrected gyro data on the basis of inertial space attitude outputted by the star sensor. According to the above joint attitude principle, the system's attitude error includes the star sensor output error and the error of the

gyro-estimated attitude under the consideration of the effects of star-sensor random error, short-period error, and gyro random drift, in which the error of relative attitude estimation by gyroscope mainly comes from the random drift of gyroscope itself and the estimation residual of constant drift of gyroscope. For the star-sensor and gyro joint attitude schemes, the factors affecting the accuracy are the random error of the star sensor, the short-period error, and the data output frequency. In case of using the high-precision gyro, the influence of random drift and measurement resolution on joint attitude determination accuracy is relatively small.

6.6.2.3 High-Stability Attitude Control Technology

The pointing information corresponding to each line of image should be strictly calculated according to the requirement of surveying and mapping accuracy. The output frequency of star sensor data is lower than the camera line frequency, and there are fewer sampling points of the optical axis pointing angle of the camera observed by star sensor, so it is mainly calculated by interpolation method. Improving the attitude stability of the satellite can improve the attitude data accuracy of the interpolation point, and then improve the image positioning accuracy.

During the stable flight of the satellite, the main factors affecting the attitude stability of the satellite are the output noise of the attitude sensor and actuator in the attitude control loop and the disturbance of the active components on the satellite. For surveying and mapping satellites, the first kind of disturbance sources mainly includes momentum wheel noise, gyro noise, attitude measurement error, and the second type of disturbance sources mainly includes the rotation disturbance of the sailboard driving mechanism and the transmission antenna. A low noise actuator is developed by using high-stability attitude control method to effectively reduce the influence of disturbance sources and improve the stability of satellite on orbit.

It can be seen from the statistics of satellite on-orbit data that the three-axis attitude stability is basically maintained within $2 \times 10^{-4}^\circ/\text{s}$. As shown in Fig. 6.8, it can meet the stability requirements of 1:50000 mapping.

6.6.2.4 Spatial Reference and Stability

The optical axis angle of the camera can be indirectly measured only by attitude sensors such as star sensor and gyroscope instead of direct measurement on orbit. Since the satellite is far from the ground, the small angular deviation between the sensor and the optical axis of the camera will lead to large image positioning error. Therefore, the stability of the relative pointing between the camera and the star sensor must be ensured when designing satellite. By integrating star sensor and camera, the structural connection path between star sensor and camera is minimized to reduce the influence of thermal deformation and ensure the relative pointing stability between them.

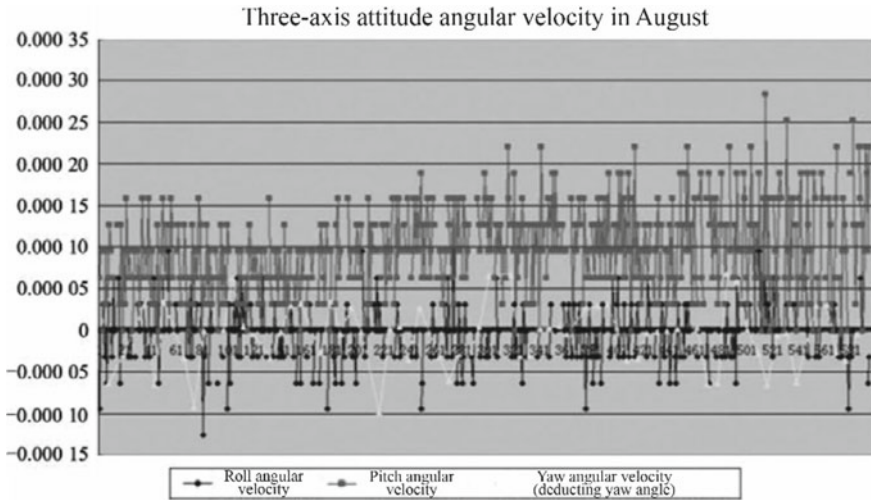


Fig. 6.8 On-orbit attitude stability change of a resource satellite

The star sensor and the camera are installed with a common reference according to the requirements of the satellite configuration, the layout of the star sensor, and FOV to ensure the pointing stability between the star sensor and the optical axis of the camera. As shown in Fig. 6.9, the influence of the intermediate connection link is reduced through the high-stability common reference board, so that the imaging reference of the star sensor and the optical camera should be as consistent as possible, and the influence of the on-orbit space environment change on the relative geometric position of the two is reduced. In addition, the integrated common reference layout of multi-star sensors ensures the joint installation accuracy of multi-star sensors by fully utilizing the inherent characteristics of single-star sensor, such as high accuracy in optical axis direction measurement and relatively low accuracy in transverse axis direction measurement.

As the key support structure connecting multiple star sensors and optical cameras, the thermal stability of star sensor board and camera board directly affect the accuracy of pointing determination of the camera optical axis, thus requiring high-stability design. In terms of materials, low-thermal expansion rate materials are generally preferred, such as carbon fiber composites, C/SiC materials, microcrystalline materials, and invar steel. In terms of temperature control, precise temperature control of the structure is an important measure to improve the stability of the structure on-orbit, because on-orbit temperature change is the main cause of the structure on-orbit deformation.

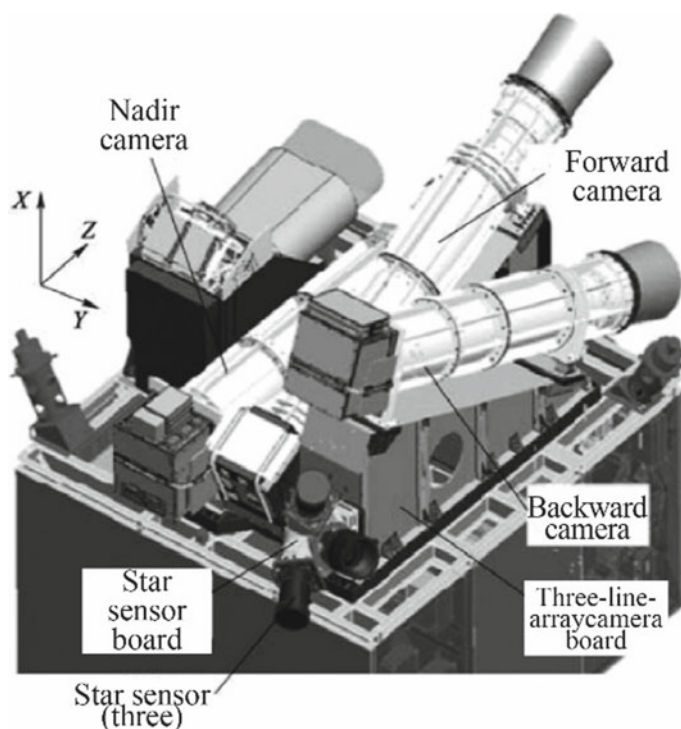


Fig. 6.9 Diagram of star sensor and camera integrated installation

6.7 High-Precision Time Synchronization Technology

Satellite time synchronization system transmits standard time signals to the subsystem of satellite synchronization time user, which enables all time synchronization users of satellite to calibrate internal time with common reference time source, thus realizing the time synchronization in whole satellite. The system consists of various electronic devices and related protocol algorithms. The satellite time system should be reasonably designed according to the requirements of satellite missions such as geometric positioning accuracy and post-processing.

6.7.1 Composition of Time System

The satellite time system mainly includes the time service part and timekeeping part. The time service part includes clock source, time transfer, and retention device. The function of the clock source is to make the time code generator count the frequency signal output from the frequency standard source to generate local time.

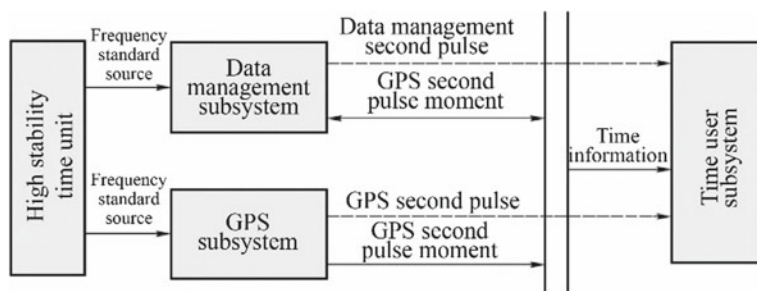


Fig. 6.10 Schematic diagram of surveying and mapping satellite time system

After comparing with the external input time reference, the reference time is output in a certain time coding format, and transmitted to the timekeeping part by the time transfer and retention device.

The timekeeping part, which is composed of the time information receiving part, the local time code generator and the application users, mainly receives the time information sent by the time service part, corrects the local time, and performs the time application. At present, the timekeeping of satellite design methods often exists in all time synchronization users on the satellite.

For high-precision surveying and mapping satellite, two sets of time systems with high precision or general precision are generally provided. The terminal using the whole satellite second pulse signal (output from GPS or digital management system) is defined as the timekeeping terminal in the high-precision time system. The terminal using only broadcast time code instead of second pulse signal is defined as the timekeeping terminal in general time system. The schematic diagram of the time system of the surveying and mapping satellite is shown in Fig. 6.10.

6.7.2 Time System Service Mode

In general precision time system, data management system counts the frequency reference signal or internal clock signal provided by high-stability time unit, generates satellite time, and publishes it in a certain period. Satellite time can be corrected by centralized, uniform, and autonomous timing.

In high-precision time system, GPS obtains time information from navigation message and realizes time synchronization with GPS. GPS outputs a pulse every second integer scale value to the user unit of high-precision time system, and transmits the absolute time information corresponding to the output second pulse to the data management system. The data management system transmits the time information to the time receiving units of each subsystem through 1553B bus.

6.7.3 Accuracy Analysis of Time System

In general precision time system, the factors affecting the time precision are high-stability time unit output accuracy, time code broadcast accuracy, and processing time delay of users in each time system because the time delay caused by the data management system itself (including software) has been eliminated before transmitting time data. The accuracy of general precision time system can reach tens of milliseconds.

For high-precision time system, GPS second pulse or data management second pulse is usually chosen as the common reference time source with timing accuracy of better than 1 μ s. The user’s timekeeping accuracy of the high-precision time system is generally better than 20 μ s, so the accuracy of the whole satellite’s time system can reach at 50 μ s, and the mission requirements of the high-precision surveying and mapping satellite can be satisfied. The accuracy analysis of time system is shown in Table 6.3.

Table 6.3 Accuracy analysis of time system of surveying and mapping satellite

Types	Items			
	Error terms	Error value	Accuracy estimation of whole satellite time synchronization	
General accuracy	High-stability time unit output accuracy (μs)	≤1	≤51 ms	
	Time code broadcast accuracy (μs)	≤50		
	General accuracy time user processing time delay (ms)	≤50		
High precision	Second pulse signal accuracy	GPS (ns)	≤300	≤20 μs
		Data management (μs)	≤1	
	Cable transmission time delay (μs) Cable transmission delay (μs)	≤0.3		
	High-precision time synchronization user time keeping accuracy (μs)	≤18		

6.8 Tie-Points Matching Technology

The tie-points matching technology includes rough matching based on imaging geometry and high-precision matching based on image texture.

6.8.1 *Rough Matching Technology Based on Imaging Geometry Relation*

For images with known imaging geometry, image matching can be achieved by using imaging geometry. Because of the errors in DEM and imaging geometry, the accuracy of matching results is generally poor, so it is rough matching. Image rough matching can provide the initial position and range information of search window for high-precision matching based on image texture. Rough matching can be divided into two steps: image simulation and the solution of the pixel correspondence between the simulated image and the high-resolution image. The process of image simulation is as follows:

- (1) For the pixels of low-resolution cameras (l_1, s_1), the coordinates of the corresponding geodetic points (l_{at1}, l_{on1}) are calculated with the help of low-precision DEM by using the forward calculation formula of the geometric imaging model of low-resolution cameras.
- (2) Using the inverse calculation formula of geometric imaging model of high-resolution camera, the coordinates of the above calculated geodetic points (l_{at1}, l_{on1}) are back-projected to the imaging surface of high-resolution camera, and the corresponding pixel coordinates (l_2, s_2) are obtained.
- (3) Because the pixel coordinates (l_2, s_2) of the high-resolution image obtained above are non-integer, a certain interpolation algorithm is used to interpolate the pixel gray level g of the pixel coordinates (l_2, s_2) through the integer gray level of the high-resolution image, and the gray value is assigned to the simulated image (l_1, s_1) pixels.

The above (1)–(3) process is repeated pixel by pixel to obtain the projection simulation image of high-resolution camera on low-resolution camera.

The process of solving the pixel correspondence between the simulated image and the high-resolution image:

- (1) For the pixels on the simulated image (l_1, s_1), the coordinates of the corresponding geodetic points (l_{at1}, l_{on1}) are calculated by using the forward calculation formula of the geometric imaging model of the low-resolution camera with the help of the low-precision DEM.
- (2) Using the inverse calculation formula of geometric imaging model of high-resolution camera, the coordinates of the above calculated geodetic points (l_{at1}, l_{on1}) are back-projected to the imaging plane of high-resolution camera, and the

corresponding pixel coordinates (l_2, s_2) are obtained, which is the corresponding high-resolution image coordinates of the simulated image.

Continuously repeating the above processes (1)–(2) pixel by pixel, all the points that are finally converted can be got, that is, the pixel correspondence between the simulated image and the high-resolution image is obtained.

6.8.2 *High-Precision Matching Technology Based on Image Texture*

Low-resolution sampling and geometric condition adjustment of high-resolution image are realized through rough image matching, and two images which can be regarded as the same resolution and geometric condition are obtained. If DEM and internal and external orientation elements are accurate, the tie-points can be obtained according to the geometric relationship. However, there are still some dislocations between simulation images and low-resolution images due to the low accuracy of DEM and the errors of internal and external orientation elements. So further high-precision registering should be performed by using image texture-based registration algorithm.

Image registration algorithms are mainly divided into two categories: region-based methods and feature-based methods. The region-based method is to process the gray level of the image as a feature, while the feature-based method is to extract certain features from the image for matching. Feature-based method is usually used for image recognition by close-range shooting. Region-based method is generally used for satellite remote sensing image matching, which mainly includes three types.

- (1) **In block matching method**, the best matching point is obtained by exploratory search based on the similarity of image gray level. Generally, it is only suitable for translation motion model, and it is mainly used in video coding.
- (2) **In gradient method**, the most successful classical algorithm is Lucas-Kanade algorithm, which is based on Taylor expansion and approximation of image, and obtains closed-form solution by minimizing the square of error. The algorithm is simple and accurate, and is widely used in computer vision and optical flow field estimation.
- (3) **Phase correlation method** is based on Fourier transform translation theorem, and with strong noise resistance and robustness and attracted wide attention, with which the isolation and extraction of translation parameters can be achieved by phase correlation. This algorithm is mostly used for high-precision matching of satellite remote sensing images.

For phase correlation method, if parabola is introduced to fit the correlation coefficients of multiple points and the vertex of parabola is taken as the best matching point, the matching accuracy of correlation coefficients can be further improved at

0.15–0.20 pixels by general parabola fitting of correlation coefficients. If the radiation distortion and geometric distortion between images are considered on the basis of correlation coefficient, the least square matching method can be developed, and the matching accuracy can be further improved to within 0.15 pixels.

The accuracy of least squares matching method is affected by the difference of matching image resolution, ground object type, and signal-to-noise ratio. The matching accuracy is 0.15 pixels of low-resolution image with 4-times resolution difference, and 0.05 pixels of low-resolution image with 16-times resolution difference. The greater the difference of visible resolution, the lower the registration accuracy is. Under different ground object conditions, the registration accuracy of water area is the lowest, followed by farmland, and the registration accuracy of urban area is the highest. The effect of SNR on registration accuracy is a nearly linear monotonic function. It is generally believed that when SNR is better than 25 times, it will no longer be the main factor affecting image registration accuracy.

6.9 Scheme Design of Three-Line Array Stereo Camera

6.9.1 System Composition and Topology

The three-line array stereo camera of the resource-3 satellite can acquire forward-view, nadir-view, and backward-view images of the same ground object, and complete the task of stereo mapping and remote sensing of resources on the scale of 1:50000 for China's territory with the obtained images and multispectral camera. The three-line array camera consists of main bodies of forward-view, direct-view, and backward-view camera; forward-view, nadir-view, and backward-view camera signal processor; three-line array camera controller and camera board. The composition block diagram is shown in Fig. 6.11.

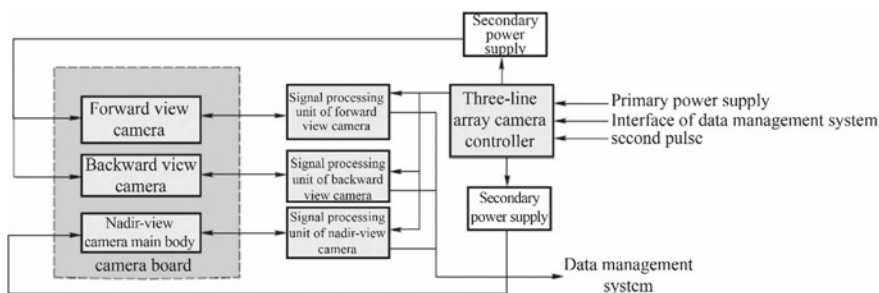


Fig. 6.11 Block diagram of three-line array camera subsystem

6.9.2 Design of Optical-Mechanical System for High-Precision Three-Line Array Camera

The main technical indicators of the three-line array camera are shown in Table 6.4. High image quality, stability lens design, and stability integrated board design are implemented according to the relevant requirements.

6.9.2.1 Design of High Precision and Stability Optical System

The transmission image space quasi-telecentric optical system is used in all three cameras of the three-line array camera subsystem, with the advantages of mature design method, simple mechanical structure, convenient processing and adjustment, and small distortion of optical system. Its structure is shown in Fig. 6.12. The focal plane components are all prism-stitched. The nadir-view focal plane component is made up of three 8192 pixel TDICCDs with a pixel size of 7 μm. The forward- and backward-view focal plane components are composed of four 4096 pixel TDI CCDs with a pixel size of 10 μm. In the nominal orbit of 500 km, the resolution of the

Table 6.4 Main technical indicators of three-line array camera

Items	Performance index
Resolution (m)	Forward-view & backward-view camera 3.5, nadir-view camera 2.1
Image width (km)	Forward-view & backward-vision 52, nadir-view 50
MTF	Forward-view & backward-vision ≥ 0.22; nadir-view ≥ 0.2 (Nyquist)
Stray light (%)	4
On-orbit stability	The image shift caused by the interior orientation element is less than 0.3 pixels, and the change of camera angle is less than 0.8 within half a year

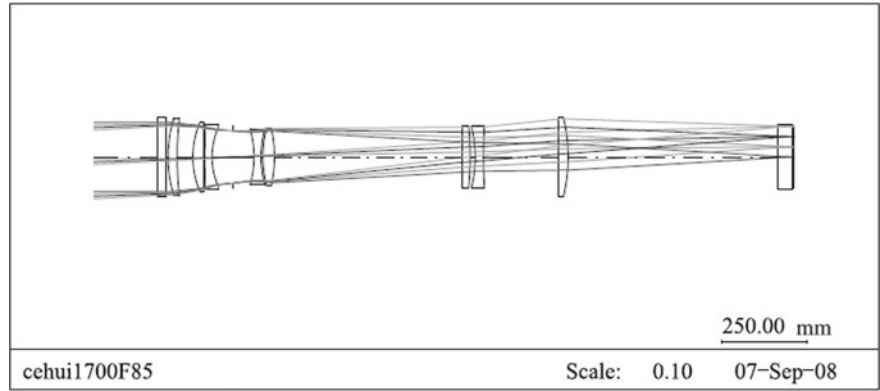


Fig. 6.12 Schematic diagram of optical system

nadir-view camera is 2.1 m @ the swath of 50 km, and the resolution of the forward- and backward-view camera is 3.5 m @ the swath of 52 km.

For the camera lens with an image space quasi-telecentric optical system, the image height is changed a little when the focal plane drifts back and forth due to temperature fluctuations, etc., because the off-axis principal ray is nearly parallel to the optical axis, thereby achieving image height stability and reducing measurement error caused by system defocusing.

The optical-mechanical structure is made of a titanium alloy, which realizes the axial and radial thermal matching design of the lens optomechanical part, so that the main body of the camera with better mechanical and thermal stability can ensure that the accurate position and image plane stability between the optical elements required by the optical system under the conditions of gravity unloading and temperature variation during on-orbit operation. Therefore, good imaging quality and stability of system parameters under spatial conditions are achieved, including the stability of the orientation elements in the system, the configuration is shown in Fig. 6.13.

High-Precision Temperature Control

The camera subsystem puts forward higher requirements on thermal control. The image quality, parameters, and variation of the camera under different thermal loads are simulated under the conditions of certain temperature level or fluctuation, axial temperature gradient, radial temperature gradient or fluctuation. The results show that the camera imaging quality can be guaranteed by precise thermal control measures.

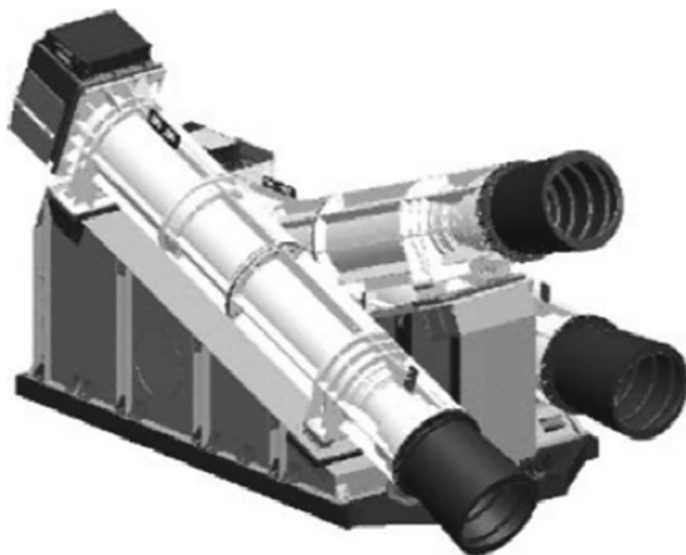


Fig. 6.13 Schematic diagram of lens structure

6.9.2.2 High Precision and Stability Integrated Board Design

The integrated board consists of one board base plate, two composite boards, two nadir-view camera boards, three flexible connectors, and several adjusting gaskets, heat insulation pads, and fastening standard parts. The composite board consists of the main body, internal and external reinforcement bars, connecting angle plates, heat insulation pads, metal flanges, and connecting inserts. The base plate connects the camera body and the star sensor through three sets of supporting parts to realize the integrated installation. In order to ensure the stability of the angle between cameras, the thermal deformation of the integrated board in the X -axis direction is controlled by the composite board component in the design and development of the integrated board scheme, the flexible sheet is used to reduce the flexible deflection of the main body of the camera, and the connection stiffness with the whole satellite is strengthened by casting magnesium base plate. Besides, the operating temperature environment of the unit assembly is precisely controlled to meet the requirement of angle stability.

6.9.3 Design of Camera Electronic System

The electronic part of the camera is mainly composed of the imaging part and the control part. The imaging part mainly includes circuit for focal plane, signal processing and data synthesis circuit, integration time control circuit, etc. The functions of driving focal plane TDI CCD, output signal buffer processing, long-line driving, filtering, gain adjustment, sampling, clamping, A/D conversion, formatting, imaging time recording, auxiliary data injection, and LVDS transmission can be realized.

The control part can realize the functions of remote-control instruction, whole second-time code, second pulse signal and service system auxiliary data receiving and transmitting, telemetry data acquisition and transmission, power distribution control for camera electronics, switching between main and backup equipment and components, locking and driving of focal plane mechanism, etc. The control part mainly includes remote control and telemetry interface circuit, CPU circuit, distribution control circuit, imaging parameter setting and state acquisition circuit (three-wire serial port circuit), focusing control circuit, etc. The electronic system framework of the three-line array camera is shown in Fig. 6.14.

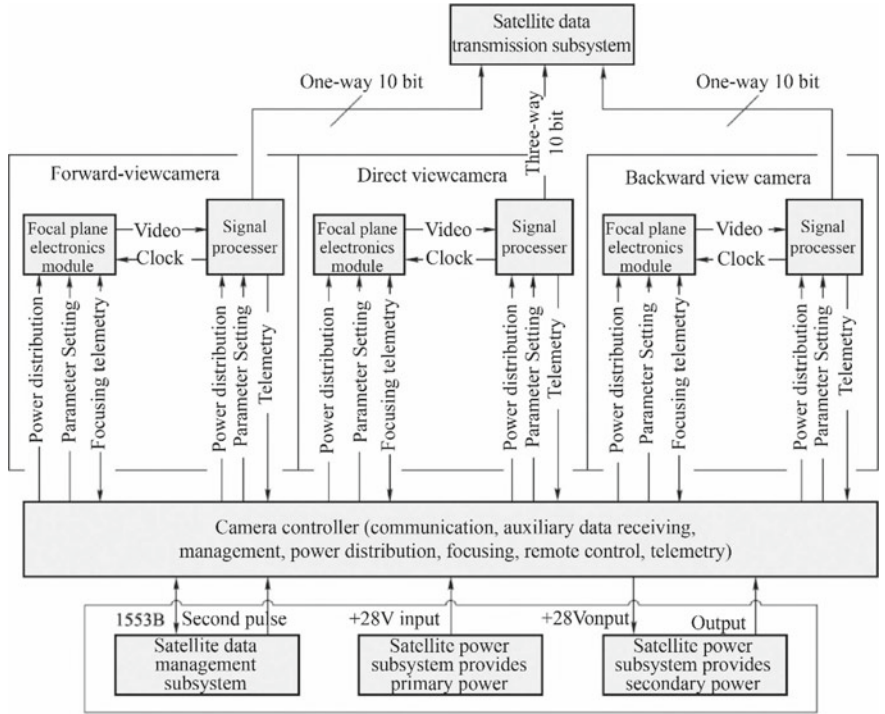


Fig. 6.14 Framework of electronic system

6.10 Geometric Calibration Technology

6.10.1 High-Precision Calibration of Interior Orientation Elements in Laboratory

6.10.1.1 Interior Orientation Elements Calibration Method

The measurement principle of internal orientation elements is shown in Fig. 6.15. As shown in the figure, N' is the rear node of the objective lens, P is the principal point position, f is the principal distance, H_i is the ideal position of the measured point, H'_i is the measured point, L_i is the image height of H'_i , and W_i is the deflection angle of the corresponding point H_i . When the lens is adjusted, the optical axis of the lens has been directed to the normal line of the camera window or the reference cube mirror. When the principal point is tested, the optical axis of the collimator is adjusted to be parallel to the visual axis of the camera, and the position of the target image on the focal plane of the camera under test is exactly the principal point.

According to the geometric relationship in the figure, the distortion calculation formula of corresponding H_i points can be expressed as

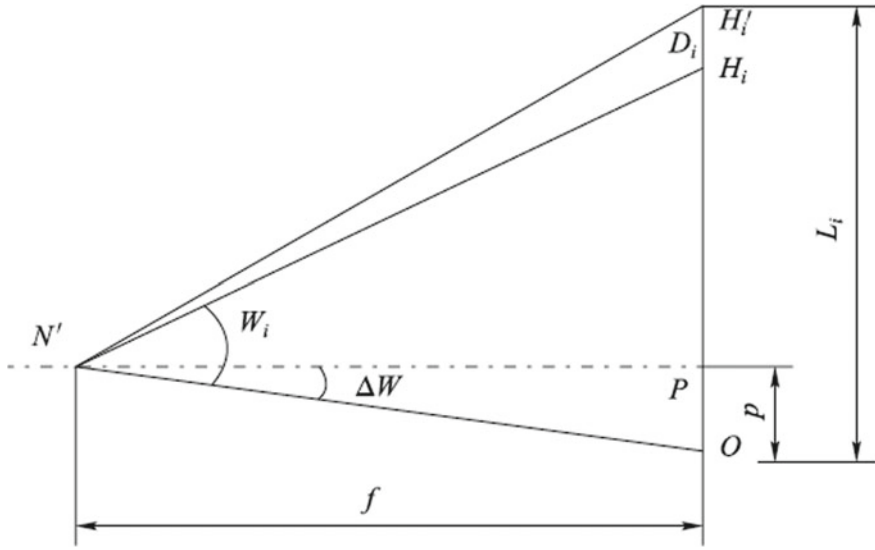


Fig. 6.15 One-dimensional internal orientation element measurement principle

$$D_i = L_i - f \tan W_i + p \tan^2 W_i. \quad (6.4)$$

In order to determine the principal distance of the camera, a reasonable solution condition is to minimize the sum of squares of distortion, which is also a common international standard solution method. Through solving the over-determined equations, the expression of the principal distance is obtained

$$f = \frac{\left(\sum_{i=1}^N L_i \tan^2 W_i \cdot \sum_{i=1}^N \tan^3 W_i \right) - \left(\sum_{i=1}^N L_i \tan W_i \cdot \sum_{i=1}^N \tan^4 W_i \right)}{\left(\sum_{i=1}^N \tan^3 W_i \right)^2 - \left(\sum_{i=1}^N \tan^2 W_i \cdot \sum_{i=1}^N \tan^4 W_i \right)} \quad (6.5)$$

According to the mass center displacement of the target image and the rotation angle W_i of the camera, the principal distance f and the distortion value D_i of the corresponding points are calculated by using the above two formulas.

6.10.1.2 Internal Orientation Element Calibration Equipment

The camera internal orientation element tester is shown in Fig. 6.16. The camera internal orientation element is tested by using the collimator target imaging.

The main test instruments and equipment of the internal orientation element are equipped as follows: the two-dimensional turntable is used to stably carry the camera to be tested, and ensure that the pupil of the camera to be tested is located at the

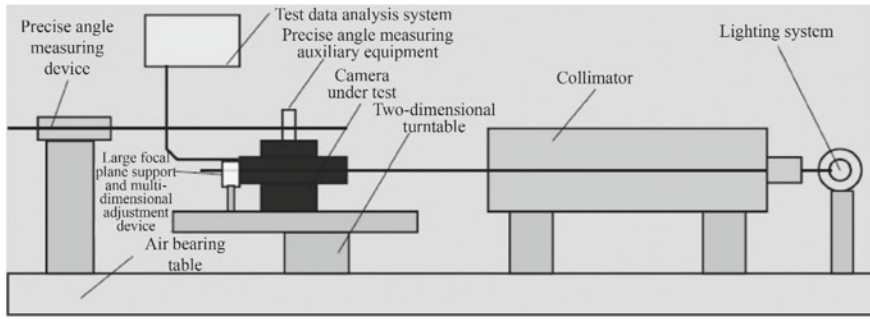


Fig. 6.16 Sketch of internal orientation element calibration

center of the vertical axis of the turntable; the photoelectric autocollimator is used to accurately measure the rotation angle of the turntable; the plane mirror is used for self-collimation with the photoelectric autocollimator; the collimator is used to provide infinite imaging conditions, the aperture is not less than the aperture of the camera to be tested, and the focal length should generally be larger than the focal length of the camera to be tested; the target is used to provide imaging light source; integrating sphere light source is selected for uniform illumination provided by illumination light source.

6.10.1.3 Accuracy Analysis of Internal Orientation Elements

(1) Accuracy Analysis of Principal Point Testing

The measurement accuracy of the principal point mainly depends on the mass center displacement error of the target image and the optical axis determination error. Optical axis determination error includes adjusting error of optical axis of collimator and lens, optical axis extraction error and focal plane installation tilting error. The combination of the above errors is the camera principal point calibration error.

(2) Principal distance test error analysis

The formula for calculating the principal distance test error is

$$\delta_f = \sqrt{\sum \left(\frac{\partial f}{\partial L_i} \right)^2 \delta_L^2 + \sum \left(\frac{\partial f}{\partial W_i} \right)^2 \delta_W^2} = \sqrt{\frac{1}{\sum \tan^2 W_i} \delta_L^2 + \frac{\sum L_i^2 \sec^4 W_i}{(\sum \tan^2 W_i)^2} \delta_W^2}, \quad (6.6)$$

where δ_L is the test error of L_i , which depends on the accuracy of the target image displacement calculation; δ_W is the test error of the angle W_i . The main distance test error can be obtained according to the actual parameters of the camera.

(3) Distortion Test Error Analysis

The test error δ_D of the distortion comes from three sources, namely the target image displacement test error δ_L , the angle test error δ_W , and the principal distance test error δ_f . The expressions are as follows:

$$\delta_D^2 = \left(\frac{\partial D}{\partial L} \right)^2 \cdot \delta_L^2 + \left(\frac{\partial D}{\partial W} \right)^2 \cdot \delta_W^2 + \left(\frac{\partial D}{\partial f} \right)^2 \cdot \delta_f^2, \quad (6.7)$$

where $\left(\frac{\partial D}{\partial W} \right)^2 \approx (-f \cdot \sec^2 W)^2 = f^2 \cdot \sec^4 W$, $\left(\frac{\partial D}{\partial L} \right)^2 = 1$, $\left(\frac{\partial D}{\partial f} \right)^2 = \tan^2 W$.

The camera distortion test errors can be calculated according to the measured camera parameters and the measurement errors of the internal orientation element test instrument.

6.10.2 On-Orbit High-Precision Geometric Calibration

High-precision geometry calibration on orbit can reliably ensure that the satellite is in optimal operating state and the geometric positioning accuracy of surveying and mapping products is improved. The calibration results are provided to the data processing subsystem for post-processing to improve the geometric quality of standard products, and then to users. The main contents of geometry calibration include image positioning accuracy, image internal distortion, geometric resolution, internal orientation element, external orientation element calibration, and load geometric stability calibration.

6.10.2.1 Internal Orientation Element Calibration Method

The calibration process of internal orientation elements includes image geometry simulation based on high-resolution aerial photographs, image MTF degradation, high precision registration of simulated and real images, solution of internal orientation elements, error analysis, etc.

6.10.2.2 Calibration Method of Exterior Orientation Elements

The calibration process of exterior orientation elements includes the measurement of tie-points and identification of control points. The results of precise orbit and attitude determination are used as the initial values of exterior orientation elements, for the establishment of error equation for exterior orientation elements, the solution of parameters to be calibrated and accuracy evaluation, etc.

6.10.2.3 On-Orbit Geometric Calibration Site

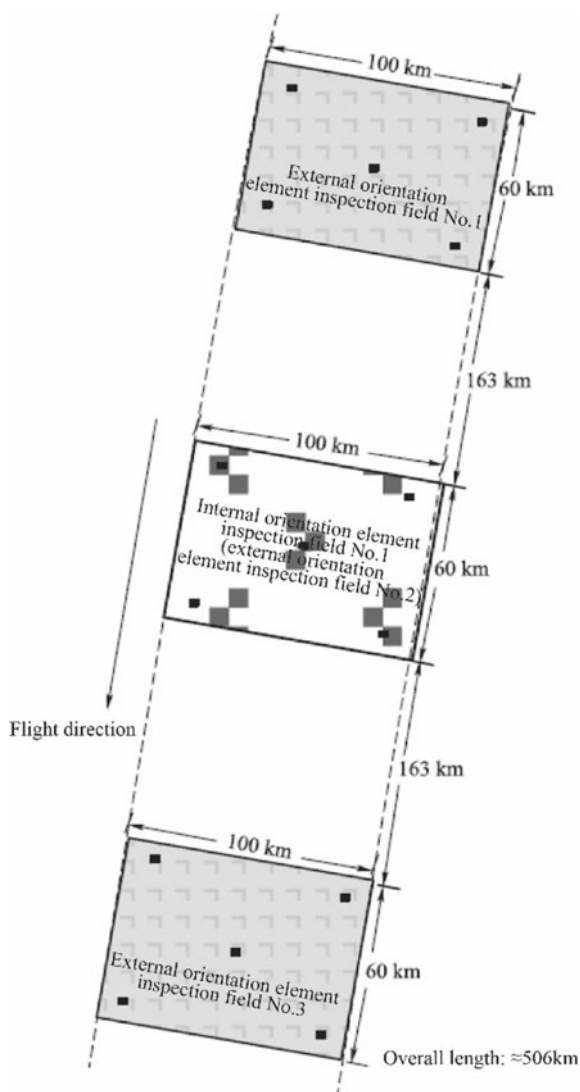
Geometric calibration and accuracy verification of high-resolution satellites on orbit using global distributed calibration fields have been widely accepted. For example, Stennis Space Center calibration field in the United States can be used for IKONOS calibration; Manosque calibration field in France; Bern/Thun calibration field in Switzerland for SPOT5 calibration; Tsukuba, Tochigi, Iwate, Tomakomai calibration field in Japan for ALOS calibration. An on-orbit geometry calibration field represented by Songshan Geometric Calibration Field in Henan Province China has been established in China, which has been used for on-orbit calibration of high-resolution remote sensing satellites such as ZY-, Mapping-, and GF-series.

On the one hand, the areas with good meteorological conditions are selected as the construction site of high-precision surveying and mapping satellite ground geometry calibration field to improve the imaging efficiency and calibration frequency of each satellite zenith passing; on the other hand, the selected areas shall be with a certain range of flat terrain, a large number of stable landmarks or ground object with obvious features, so as to facilitate the selection of ground control points in order to meet the requirements of laying targets, calibrating interior/exterior orientation elements and radiation calibration. The basic conditions of calibration field are

- (1) with Data of Digital Surface Model (DSM), Digital Elevation Model (DEM), and Digital Orthophoto Model (DOM) data with specific scale, which are generated by post-processing the acquired high-resolution aerial photographic stereo data that can cover the calibration field;
- (2) with centimeter-level high-precision ground control points, which is input condition for satellite geometry calibration, and established by means of GPS measurement. Based on the control point network with uniform distribution and high accuracy, high-precision geometry calibration of surveying and mapping satellites can be achieved;
- (3) with good climatic conditions, which can ensure the availability of calibration field.

As shown in Fig. 6.17, the Geometric Calibration Field Songshan in Province Henan, China, is located in the central part of China with overall area of about 10,000 km²; the elevation from 100 to 1500 m; the diverse main landforms such as plains, hills, and mountains, multiple reservoirs with various sizes; representative vertical and horizontal railway trunk lines (including high-speed rail), highway network, national highway, communication trunk line and various pipe network; and representative climatic characteristics, under which the effective time is guaranteed for acquiring high-quality optical remote sensing images. In the site Songshan, there is a large-scale positioning reference station and a high-precision ground control point network covering the experimental site. Among them, 69 high-precision control points (plane accuracy 0.1 m, elevation accuracy 0.2 m) are distributed in 8000 km², which are used for space remote sensing calibration and testing with natural and artificial landmarks. The site Songshan has high precision and high-resolution digital surface model, digital elevation model, and local data of digital orthophoto map.

Fig. 6.17 Schematic diagram of the geometric calibration site Songshan, Henan, China



6.10.2.4 On-Orbit Calibration Accuracy Analysis

The key of satellite geometry calibration lies in the solution of bias matrix. The so-called bias matrix is the rotation matrix between the sensor coordinate system and the satellite platform coordinate system caused by the installation error between the sensor and the satellite platform. It is used to correct the imaging deviation caused by the non-coincidence between the sensor and the satellite platform coordinate system. In the image pre-processing of surveying and mapping satellite, the positioning error of sensor relative to the satellite platform is corrected by calculating the bias matrix,

and the geometric positioning accuracy is thereby improved. In practice, the orbit and attitude measurement errors are merged into the rotation matrix between the sensor and the satellite platform to solve the problem.

Since GPS measures the position of GPS phase center and star sensor measures the pointing direction of star sensor in J2000 coordinate system, the data of GPS and measured by star sensor shall be converted into the position and orientation of satellite to get the position and attitude of satellite. Therefore, three offsets $[D_x D_y D_z]^T$ of the GPS phase center in the satellite body coordinate system, the coordinate rotation relationship R_{Bodystar} between the star sensor body system and the satellite body system, the installation matrix of camera on the satellite platform $R_{\text{Bodycamera}}$ and $[d_x d_y d_z]^T$, and the orientation angles (ψ_x, ψ_y) of each pixel in the CCD linear array in the camera coordinate system shall be measured. Without considering the influence of atmospheric refraction, a rigorous imaging geometric model of high-resolution optical remote sensing images can be constructed.

$$\begin{aligned} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{\text{WGS84}} &= \begin{bmatrix} X_{\text{GPS}} \\ Y_{\text{GPS}} \\ Z_{\text{GPS}} \end{bmatrix} + m R^{\text{WGS84J2000}} R^{\text{J2000star}} (R^{\text{Bodystar}})^T \begin{bmatrix} D_x \\ D_y \\ D_z \end{bmatrix} \\ &+ \begin{bmatrix} d_x \\ d_y \\ d_z \end{bmatrix} + R^{\text{Bodycamera}} \begin{pmatrix} \text{tg}(\psi_y) \\ \text{tg}(\psi_x) \\ -1 \end{pmatrix} \cdot f, \end{aligned} \quad (6.9)$$

where $[XYZ]_{\text{WGS84}}^T$ represents the three-dimensional Cartesian coordinates of the ground point P under WGS84, m is the proportional coefficient, and f is the camera principal distance.

Through the model analysis, it can be found that the errors affecting the geometric positioning accuracy of surveying and mapping satellite images mainly include the camera internal distortion error, the GPS observation error, the attitude observation error, and the camera installation angle error. In addition, the accuracy of satellite on-orbit calibration is affected not only by the above-mentioned satellite correlation error (the influence of random error is greater), but also by the accuracy, number and distribution of ground control points of the ground geometry calibration field itself.

After on-orbit geometry calibration, the uncontrolled positioning accuracy and internal geometric accuracy of the ZY-3 satellite image have been significantly improved, in which its uncontrolled positioning accuracy has increased from about 1500 m before calibration to less than 15 m after calibration. The on-orbit geometry calibration accuracy of ZF-3 is better than 0.3 pixels. After geometry calibration, better plane and elevation accuracy can be achieved by only a control point. With the increase of control points to more than four, the plane and elevation accuracy tends to stability, and reaches at about 4 m and about 2 m, respectively.

6.11 High-Precision Surveying and Mapping Processing Technology and Flight Test Results

Bundle adjustment is the most rigorous and precise adjustment method in photogrammetry, which takes each spatial ray as the basic adjustment unit. Through rotation and translation of each ray, the bundle corresponding to the same tie-point intersects optimally with the control point coordinate as the reference, the image exterior orientation elements and the coordinates of the encrypted points are obtained by calculation to realize the adjustment measurement. The basic equation is an imaging geometric model based on collinear conditional equation. Due to the particularity of push-broom imaging of satellite sensors, the external orientation elements are highly likely to cause strong correlations and lead to substitution effects between unknown parameters, which often make the least squares unable to converge to the correct solution. For this reason, the position and attitude information of sensors measured on the satellite can be introduced into the adjustment system as weighted observations to ensure the correctness and stability of parameter solution. Bundle adjustment with a strict imaging model can truly reflect all kinds of error sources in the imaging process, but its form is more complicated and not universal in practice.

RPC model is a general geometric model of optical remote sensing image with parameter generated by a piecewise fitting process, which is the key link between ground pre-processing and application of optical image. According to the study of RPC model, the linear term of rational function polynomial represents the error caused by optical projection system, the quadratic term for the error caused by Earth curvature, atmospheric refraction and lens distortion, and the cubic term for other unknown errors with higher order components. Therefore, the errors exceeding the third-order components cannot be replaced by high accuracy of RPC model.

From February 20 to April 10, 2012, during the on-orbit test of the satellite ZY-3, China Satellite Surveying and Mapping Application Center (SASMAG) used the existing control data and RPC model to generate DEM, DOM, and Digital Line Graph (DLG). The results show that the RPC model can completely replace the rigorous model to carry out mapping task. The mapping accuracy of ZY-3 meets the requirements of 1:50000 stereo mapping accuracy and 1:25,000 revision survey accuracy. For details, see Table 6.5.

6.12 Application of Stereo Surveying and Mapping Satellite

Due to its unique high elevation accuracy, stereo surveying and mapping products play an important role in many fields including map production, navigation, land resources survey, and environmental monitoring.

Table 6.5 Area mapping accuracy of ZY-3 on-orbit test

Survey area	Testing products	Plane error (m)	Elevation error (m)	Specification requirements (m)			
				1:50000		1:25,000	
				Plane	Elevation	Plane	Elevation
Harbin survey area(Flat) Yan'an survey area	DLG	4.67	1.18	25	2.5	12.5	1.2
	DEM	—	1.27	—	4	—	2
	DOM	3.04	—	25	—	12.5	—
(Mountain) Aba survey area	DLG	7.72	3.18	37.5	6.0	18.75	3.0
	DEM	—	4.43	—	11	—	5.5
	DOM	4.73	—	37.5	—	18.75	—
Harbin survey area (Alpine)	DEM	—	2.77	—	19	—	9.5
	DOM	2.37	—	37.5	—	18.75	—

6.12.1 Basic Geographic Surveying and Mapping

DLG, DEM, DOM can be produced by using the forward-view and backward-view cameras of the surveying and mapping satellite in combination with a small amount of ground control point orientation or regional network adjustment, which can meet the accuracy of map in 1:50,000, and is more suitable for making basic data such as 1:50,000 topographic map. The main products include

- (1) **DLG** is a geographic information data set which expresses terrain elements in the form of vector data. DLG includes both spatial information and attribute information, which can be used in construction planning, resource management, investment environment analysis, and as a spatial positioning basis for various professional information systems such as population, resources, environment, transportation, and public security.
- (2) **DEM** is a data set of ground fluctuations expressed by elevation values of regular grid points. DEM can be used to make perspective and section maps, to calculate earthwork and surface coverage area, and to analyze topographic morphology, visual condition, and flood submerged area related to elevation.
- (3) **DOM** is an image data set corrected by orthophoto projection. DOM has rich and intuitive information, good interpretability and measurability, from which natural geography and socioeconomic information can be directly extracted.

The standard DSM formed by the satellite image in combination with the digital elevation can describe the height distribution characteristics of the surface in detail. It not only contains the DEM data of the terrain, but also covers the elevation information of the surface objects, see Fig. 6.18.

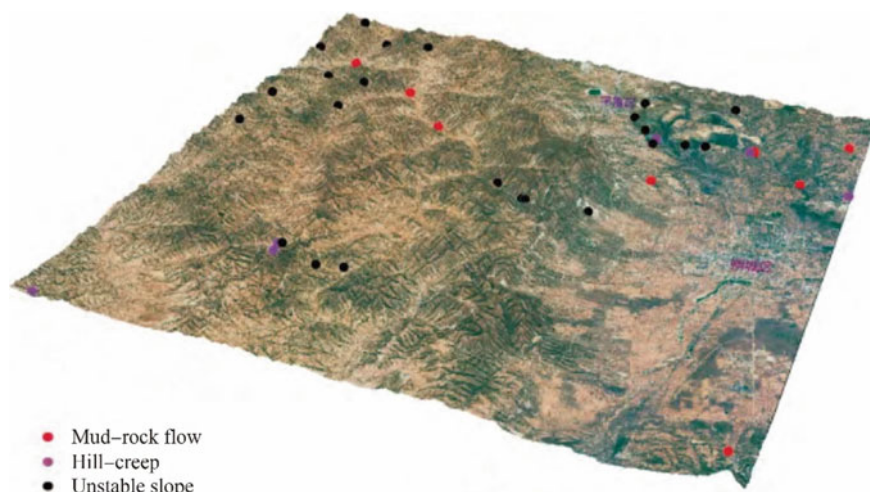


Fig. 6.18 3D model image of study area

6.12.2 Surveying and Mapping of Islands and Reefs

With the gradual expansion of China's marine rights and interests, the establishment of high-precision three-dimensional reference framework, deep-sea exploration, precise seabed topographic mapping, accurate positioning and mapping of islands, accurate coastline measurement, reef identification, data integration and fusion of multi-source heterogeneous massive marine surveying and mapping have become important research directions. Using surveying and mapping satellites to monitor the geographic information mapping and geographical environment of China's coastal zones and islands and to establish a unified land-sea marine geodetic reference framework are the necessary basis for ensuring China's marine rights and interests.

Through the use of surveying and mapping satellite images, the key technologies of surveying and mapping of islands (reefs) which are unreachable and far away from the mainland have been broken through. Finally, the technical difficulties of constructing surveying and mapping reference of islands (reefs) which are consistent with the land have been solved, and the advanced modern technology and method system of surveying and mapping of islands (reefs) has been established, which provides data assurance for China's marine strategy, see Fig. 6.19.

6.12.3 National Geographical Situation Monitoring

Using the archives of surveying and mapping results in different periods, the geographical elements such as nature and humanity are monitored in dynamic, quantitative, and spatialized mode, and the change, frequency, distribution characteristic,



Fig. 6.19 Image of China’s islands and reefs. Reprinted from Ref. [1], copyright 2017, with permission from Satellite Applications

regional difference, and trend are statistically analyzed, thus forming monitoring data, maps, and research reports reflecting the spatial distribution and development and change laws of various resources, environmental, ecological, economic factors have been formed, see Fig. 6.20.

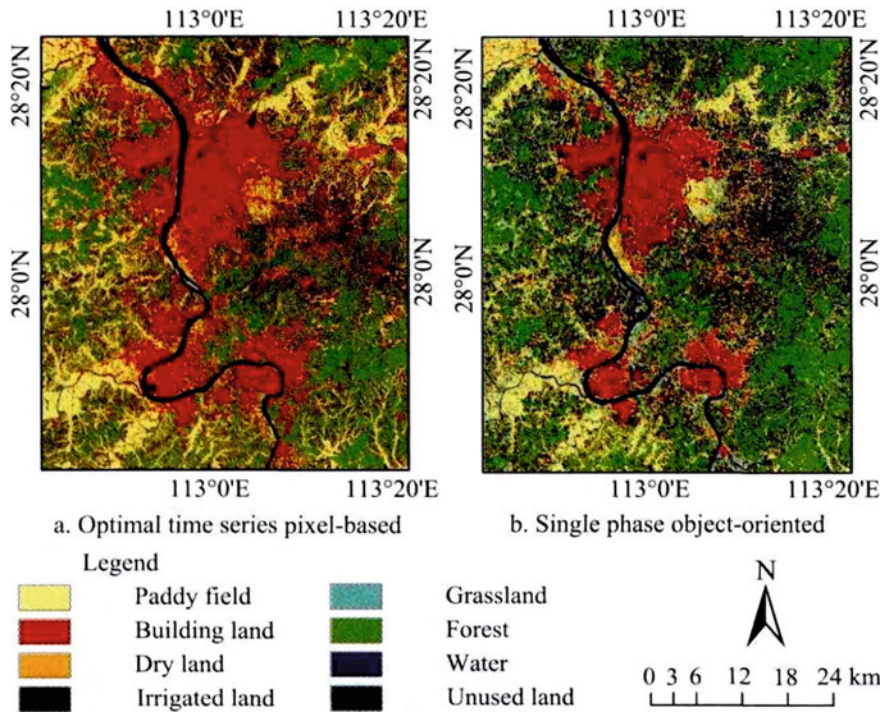


Fig. 6.20 Classification result with optimal time series pixel-based and single-phase object-oriented

6.13 Conclusion

Providing all-day geographic information services to the society and the public is the fundamentals of the development of surveying and mapping industry in the new era. Under such circumstances, space surveying and mapping satellite industry will surely follow the trend, face difficulties and accelerate the continuous, real-time, fast and accurate acquisition of image products and high-precision auxiliary data on a global scale. In addition, the improvement of China's industrial basic capacity will continue to promote the development and performance improvement of satellite components such as star sensor, gyroscope, and payload. With a larger scale space-based mapping capability, the scale and data accuracy of space mapping will be further improved, and the application level of surveying and mapping products in the national geographic information service, map navigation industry and disaster prevention and mitigation will be enhanced.

Reference

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Chapter 7

Design and Analysis of High-Resolution SAR Remote Sensing Satellite System



7.1 Overview

Since the space-borne Synthetic Aperture Radar (SAR) is not affected by weather and climate, and can perform large-area Earth observation around-clock, all weather and with high resolution, it has become an important technical means for Earth observation and has been widely used in various fields of the national economy, such as ocean condition monitoring, geological surveys, agriculture, water conservancy, and disaster surveillance.

SAR breaks through the limitations of traditional optical sensors, which are susceptible to weather and other external conditions. It can work all day and all weather. Moreover, the microwave signal with abundant characteristics contains phase, amplitude, and polarization information. SAR image can better compensate for the obvious weak points of traditional optical imaging. Compared with optical imaging methods such as visible light and infrared, SAR imaging targets in microwave band (P/L/S/C/X/Ka, etc.), the target parameters detected are related to the backscattering characteristics, while optical imaging is to image a target through visible light, infrared, etc., and the target parameter detected is the reflection or radiation characteristic of the target. Like the visible light band, SAR is easy to achieve high spatial resolution (sub-meter level), and SAR imaging can achieve multi-band, multi-polarization, Ground Moving Target Indication (GMTI), interference, and differential interference imaging modes. It can be seen that SAR and optical imaging are widely used. Two different imaging systems can achieve complementary on information, and the effect will be multiplied through the fusion of both systems.

This chapter focuses on the system design method of high-resolution SAR imaging satellite system orienting to imaging quality application requirements, including system design elements, high-precision imaging quality control, imaging positioning accuracy analysis, radiation and geometric calibration, SAR data processing and inversion technology, etc.

Table 7.1 Typical high resolution of space-borne SAR system

Satellite	Country/Region	Launch time	Band	Resolution/m	Imaging swath/km	Main operation modes
SAR-Lupe	Germany	2006	X	0.5	10	Strip map, spotlight
Terra-SAR	Germany	2007	X	1–16	10–100	Scan, spotlight
Cosmo-Skymed	Italy	2007	X	1–4	10–60	Strip map, spotlight
Sentinel-1A	Europe	2014	C	5	20	Spotlight, strip map, scan
Radarsat-2	Canada	2007	C	3	20	Spotlight, strip map, scan
ALOS-2	Japan	2014	L	1–10	25–70	Spotlight, strip map, scan

7.1.1 Overview of Development

Since the successful launch of the first space-borne SAR satellite, Seasat-1, in 1978, many countries have carried out research on space-borne SAR technology. Especially in the past ten years, with growing attention to multi-dimensional spatial information in the world, space-borne SAR has become a hot research topic in the field of Earth observation. The United States, Russia, Europe, Canada, Israel, Japan, China, and other countries or regions have launched SAR imaging radar satellites for different applications. At present, the spatial resolution of SAR satellite imaging can reach 0.3–1.0 m or even higher, and the relative accuracy of Digital Elevation Model (DEM) can reach 2 m (Table 7.1).

7.1.2 Development Trend

Through the comprehensive analysis of the current development status of satellite-borne SAR satellite technology, the following enlightenments can be drawn:

- (1) **Space-borne SAR spatial resolution is further improved.** The spatial resolution indicators of Terra-SAR and SAR-Lupe in Germany, Cosmo-Skymed in Italy, Radarsat-2 in Canada, and China’s GF-3 experimental model have been improved to 0.5–1.0 m.
- (2) **Space-borne SAR has developed in parallel with various imaging technology systems.** Most of the space-borne SAR uses planar antenna, which can

easily realize electronic scanning and digital beam forming, but it has some shortcomings such as heavyweight and high power consumption. The design of reflector antenna combined with feed can greatly reduce the quality of radar system, but it has higher requirements for reflector accuracy.

- (3) **Future space-borne multi-band SAR technology.** Through the research and development of multi-band lightweight SAR antenna and multi-band SAR imaging system, a satellite and a set of SAR systems have the ability of multi-band imaging at the same time, and complete the high resolution and wide coverage Earth observation tasks.

7.2 Demand Analysis and Technical Characteristics

The development of high-resolution SAR satellites can complement the high-resolution optical remote sensing satellites, and build a comprehensive Earth observation system with all-day, all-weather, high-efficiency, wide coverage, multi-scale, and multi-source remote sensing information. As an important means of remote sensing, SAR has immense application value in various fields of national economy.

7.2.1 Task Requirement Analysis

Space-borne SAR can be used for land resource surveys, disaster assessments, marine research, and environmental monitoring applications.

In the application of disaster prevention and mitigation, disaster-causing factors are monitored through long-time series observation of disaster-inducing environment. HEO SAR satellite can be used for staring observation on hot spots, continuously and dynamically monitor the changes of flood submergence area, landslide, debris flow, barrier lake, etc. In earthquake emergency rescue, high-resolution and high-frequency observation is carried out for building collapse, traffic facilities destruction, secondary disasters of earthquakes, etc., which provides guarantee for decision-making of earthquake emergency rescue.

In the application of land transportation, the large-scale wide swath imaging characteristics of space-borne SAR satellite can be used to detect the water system characteristics, surface water distribution, flood area, soil moisture, land use, vegetation cover, and other environmental resources. Space-borne SAR satellite is also used to detect ocean internal waves, waves, fronts, sea surface wind fields, shallow underwater topography, oil spills, sea ice, green tide, coastal zone, and sea surface targets (surface ships, reef artificial facilities, offshore oil platforms, etc.).

7.2.2 *Technical Characteristics of Microwave Imaging Satellite*

7.2.2.1 With the Increasing Resolution of Space-Borne SAR, the Size of SAR Antennas is Growing

As resolution requirements continue to increase, the aperture of the SAR antenna is getting larger and larger, and its precision is getting higher and higher. Large-aperture antenna needs to consider the limitation of system volume and weight. The smaller size of antenna and microwave components required can meet the work requirements in X band or higher, but the higher accuracy of antenna reflector is needed. When the satellite is working on orbit, especially for large-aperture reflector antenna, it is difficult to maintain high reflector precision. The more complicated configuration of the large-aperture SAR antenna is characterized by the weak stiffness, low fundamental frequency, dense mode, and large moment of inertia, whose proportion in the whole satellite's inertia is larger.

7.2.2.2 The Space-Borne SAR Payload has Various Imaging Modes, Large Peak Power, and High Requirements on the Platform Power System

The basic imaging modes include spotlight mode, striping mode, and scanning mode, each with different operating characteristics, time, and power requirements. So, the power supply system shall meet its huge peak power demand. The SAR satellite payloads with T/R module or solid-state amplifier all work with different Pulse Repetition Frequency (PRF). Pulse operation of high-power SAR payload will bring great interference to the system, which will increase the ripple of power supply bus and reduce the stability of the system. To ensure the power supply safety of platform and load equipment, the power supply system should have strong ripple suppression and absorption capacity.

7.2.2.3 The Space-Borne SAR Payload has a Large Average Heat Consumption and is Difficult to Dissipate Heat

Although SAR payloads usually work intermittently, the average heat consumption under the steady state is also very large. Considering the installation location of these equipments, the external heat flow of orbits, and the heat of other large heat consumption devices on the satellite, the satellite payload module will come under enormous heat dissipation pressure. The extremely concentrated distribution of heat consumption over time results in that the transmitter with relatively high heat consumption and low heat capacity comes under pressure of drastic temperature rise during operation. Temperature stability is a prerequisite for ensuring SAR payload imaging quality.

Therefore, it is another difficult problem for thermal control design of payload to substantially reduce the temperature fluctuation during the operating period of load equipment.

7.2.2.4 High Precision and High Stability Control are Required for SAR Satellite

Different from optical remote sensing and other satellites, the pointing of large flexible antennas has large deviation from the satellite platform, and this error has many frequency components under the influence of thermal environment, solar pressure, etc. The attitude determination result of star sensor gyroscope will cause poor image positioning accuracy. However, it takes a lot of manpower and material resources to improve the positioning accuracy through ground calibration. It is required to calibrate the satellite on the ground all the time during its life cycle. For areas lacking calibration points on the ground, such as oceans, unmanned areas, and offshore locations, it is hard to ensure high positioning accuracy. In this way, both the satellite and the antenna are required to have the capability of high precision and high stability control.

7.3 Key Design Elements of Space-Borne SAR Imaging Quality

Because there are many mutually constrained factors affecting the imaging quality of SAR satellite, such as satellite platform, SAR payload, and ground information processing, it is necessary to analyze the satellite-ground integration mission of SAR satellite system and optimize the overall indicator of SAR satellite system on the basis of considering various engineering error factors. SAR satellite-ground integrated imaging quality indicator can be divided into two categories: the indicator describing image radiation performance and the indicator describing image spatial performance.

7.3.1 Radiation Imaging Quality

- (1) **System sensitivity** is expressed by the noise equivalent backscattering coefficient $NE\sigma_0$, which determines the sensitivity and imaging capability of the SAR system to weak targets, that is, the minimum backscattering coefficient of the target that can be reliably detected by the SAR system under a certain SNR requirement. If the backscattering coefficient of the target is less than the

scattering coefficient, the energy reflected by the target will be lower than the system noise, and the SAR system cannot effectively detect the existence of the target.

- (2) **Radiation accuracy** reflects the ability of quantitative remote sensing of SAR system, which can be divided into relative and absolute radiation accuracy. Relative radiation accuracy refers to the standard deviation of the known target backscattering coefficient error in one imaging time. Absolute radiation accuracy refers to the root mean square error between the measured and real values of the target backscattering coefficient in different positions of radar image. SAR system requires radiation correction, which usually includes calibrations inside and outside the system. Radiation accuracy is an indicator to measure the accuracy of radiation correction.
- (3) **Radiation resolution** characterizes the ability of SAR system to distinguish the backscattering coefficients of different targets in the imaging range. It is related to the parameters of radar system and the SNR and equivalent visual number of images in the processing. This parameter is a measure of image quality grade, which directly affects the ability of interpretation of space-borne SAR images.
- (4) **Ambiguity** of SAR satellite signal refers to the mixing of nonhuman interference spurious echo signal (ambiguous signal) and useful echo signal in addition to the observed useful signal, thus forming a false target in the image. Image ambiguity is divided into the azimuth ambiguity and the range one, which mainly affects the accuracy of target interpretation and the ability of describing target details.
- (5) **Peak Sidelobe Ratio (PSLR)** is defined as the ratio of peak value in the sidelobe region of point target impulse response to peak value of main valve. It is divided into peak sidelobe ratio in azimuth direction and peak sidelobe ratio in range direction. The magnitude of PSLR determines the cover degree of strong target echo sidelobe to weak target.
- (6) **Integral Sidelobe Ratio (ISLR)** is defined as the ratio of sidelobe energy to main lobe energy of point target impulse response, which quantitatively describes the extent to which a partially darker region is submerged by sidelobe energy from surrounding bright region.

7.3.2 Geometric Imaging Quality

- (1) **Ground resolution** is the key indicator to determine the spatial resolution ability, which is directly related to the type and probability of target detection and recognition by interpreters. In terms of demand, the resolution should be improved as much as possible to ensure the ability of target recognition and verification.
- (2) **Positioning accuracy** should be improved as much as possible in the absence of control points.

- (3) **Imaging swath** is an important indicator of satellite, which largely determines the imaging efficiency of satellite. The imaging can range from tens to thousands of kilometers. Under a certain spatial resolution, the wider the imaging swath, the better.
- (4) **Incidence angle** is the angle between the line connecting the SAR satellite to the target point and the normal line of the Earth's surface at that point. The selection of the incident angle range of satellite system should consider imaging range, revisit time, image indicator optimization, and system sensitivity.

7.4 Design and Analysis of Space-Borne SAR Payload

7.4.1 Principle of SAR Imaging

SAR is a microwave imaging payload. The geometric relationship of its imaging process is shown in Fig. 7.1. During flight, SAR transmits linear frequency modulation signals with the product of large time-bandwidth to irradiate the imaging region in its period of Pulse Repetition Time (PRT). In the synthetic aperture time, every target in the scenario is irradiated by repetitive emission pulses, which is equivalent to using a much larger aperture (i.e., the synthetic aperture length of the radar antenna) than the real antenna to observe the target area in the course of radar motion.

Matched filtering and coherent superposition are applied to the acquired SAR echo data in range direction and azimuth direction, respectively, to obtain the scene

Fig. 7.1 SAR imaging schematic diagram

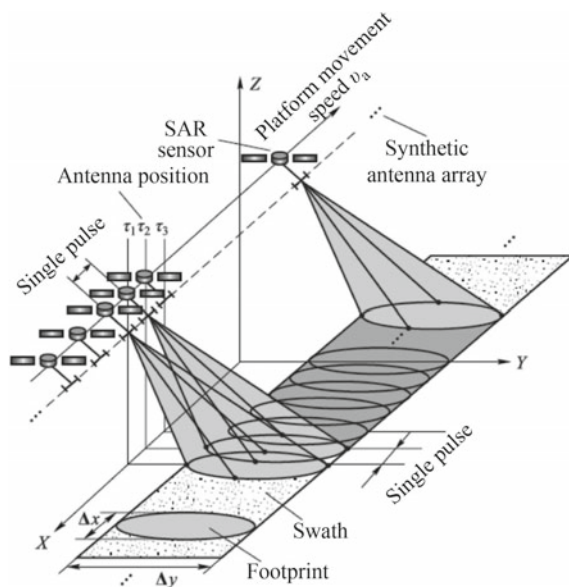


image corresponding to the data. The slant resolution of SAR can be calculated by the following equation:

$$\rho_r = \frac{c}{2B}, \quad (7.1)$$

where c is the velocity of light and B is the bandwidth of the transmitting signal.

The SAR theoretical azimuth resolution formula is as follows:

$$\rho_a = \frac{D}{2}, \quad (7.2)$$

where D is antenna length in azimuth direction.

In the case of synthetic aperture, the range resolution of SAR is related to the signal bandwidth, and the azimuth resolution is independent of the wavelength and the location of the target and is equal to half of the actual antenna aperture. Therefore, SAR can greatly reduce the dependence of resolution on target environment. Theoretically, good resolution can be obtained as long as the signal bandwidth can be increased and the antenna aperture of radar can be reduced. Practically, the transmitting and receiving power of the radar antenna is related to the area of the radar antenna, and the beam width is also related to the azimuth direction of the radar aperture. The radar antenna aperture cannot be reduced indefinitely.

7.4.2 SAR Antenna Design

7.4.2.1 Selection of Antenna System

Satellite-borne SAR antennas can adopt both reflector and phased array antenna systems.

The reflector antenna system is mainly composed of reflector and feed system, which can be divided into symmetrical reflector antenna and biased reflector antenna according to the antenna structure, or divided into single reflector, double reflector, and multi-reflector antenna in terms of the number of reflectors. Focus offset fed antenna is composed of many fixed antenna radiation units. These radiation units can be fed coherently. By controlling the amplitude and phase of each radiation unit, the beam direction can be changed rapidly to form a specific pattern to meet different application requirements.

Phased array antenna combines space radiation and receiving beams through real-time control of the antenna transmitted signal phase, and realizes flexible beam scanning and beam forming. Phased arrays are available in flat and reflector forms. The radiation source of the reflector antenna is in the form of a phased array that transmits and receives radar waves through the reflector. This type of antenna has the advantages of lightweight, etc., but the ability of beam scanning is limited. It

is usually required to drive the reflector scanning as a complement to realize wide-range beam scanning. However, the mechanical scanning device is complicated and the scanning mode is not flexible.

Flat phased array antenna has the advantages of easy beam forming, flexible beam scanning, and high reliability of electronic control, which is conducive to wide-range scanning of radar beams. However, the antenna is heavy and the satellite is required to provide a larger mounting surface.

7.4.2.2 Radiation Array Design

The radiating array of an SAR phased array antenna is usually in the form of a microstrip patch antenna or a waveguide slot antenna. Both radiating antenna array forms have their own advantages and disadvantages: in terms of electrical performance, the radiation efficiency of the microstrip patch antenna is relatively low, 40–50%; the waveguide slot antenna has high radiation efficiency, which can reach 60–70%; in terms of weight, the traditional metal waveguide slot antenna has a large weight, but the weight of the antenna radiation surface can be reduced by means of structural optimization design.

7.4.2.3 Band Selection

Statistical results of remote sensing applications and SAR application bands are shown in Table 7.2 (including Ku band for airborne SAR). In the four bands of L,

Table 7.2 Optimal operating frequency band of SAR system for various remote sensing observation projects

Remote sensing observation item	Optimal operating frequency band	Remote sensing observation item	Optimal operating frequency band
Soil moisture	L, C	Sea wave	L, C
Crop growth status	C, X, Ku	Seawater pollution	C, X, Ku
Crop identification	X, Ku	Coastal change	L, C, X
Farmland boundary	C, X, Ku	Algae surveillance	X, Ku
Natural vegetation	C, X, Ku	Iceberg movement	C, X
Forest state	L, C, X	Ice coverage	C, X
Irrigation	C	Precipitation	C
Marine hurricanes	L, C	Ocean current	L, C
Water pollution	C, X, Ku	Geological structure	L
Snowstorm	C, X	Land surveying and mapping	C, X
Hydrology	L, C		

C, X, and Ku, there are eight remote sensing projects suitable for L band, 18 remote sensing projects for C band, 13 remote sensing projects for X band, and seven remote sensing projects for Ku band.

7.4.2.4 Design of Polarization Operating Mode

Space-borne SAR generally uses linear polarization, including Horizontal (H) polarization and Vertical (V) polarization and a variety of combinations. There are many ocean and terrestrial observation targets. The specific single polarization method is very effective for the observation of specific targets, but it cannot observe the most targets at the same time. For example, HH and VV polarization are required for frontal and eddy monitoring, HV polarization for sea ice monitoring, HH, HV, VH, and VV polarization for ship monitoring, HH, HV, VH, and VV polarization for drought monitoring and ecological environment monitoring. Multi-polarized SAR can provide the third dimensional information besides the magnitude and phase of the observed target. Radar echoes with different polarizations have different observation effects for different observation elements, which can improve the detection and inversion accuracy of observation elements.

Multi-polarization can meet the needs of users in different industries. For the observation of sea wave and sea surface wind field, the spectral data extracted from HH and VV polarization SAR images are complementary and can improve the inversion accuracy under different sea and topographic conditions; for sea ice monitoring, the accuracy of sea ice classification can be improved by using multi-polarization data; for sea surface target recognition and coastal vegetation classification, multi-polarization SAR has a good effect.

7.4.2.5 Antenna Size Design

According to the imaging principle of space-borne SAR, the area and size of SAR antenna are limited by many factors, such as ambiguity of range and azimuth, azimuth direction resolution, and beam coverage. In addition, the limitations of platform power consumption and platform installation should also be considered. The smaller the antenna area is, the larger the power consumption will be. The envelope size, especially the height and width of the folded large-aperture antenna should meet the installation requirements of the platform.

7.4.3 Design of Incident Angle

Different radar incidence angles have different effects on different ocean targets. Regardless of HH polarization or VV polarization, the backscattering cross section decreases with the increase of the incident angle. Therefore, from the angle of return

energy, the minimum angle in the applicable range of Bragg scattering theory should be chosen as far as possible, generally in range of 20° – 30° .

From the application point of view, different radar incidence angles have different observation effects on different ocean or land targets. The range of incidence angle from 20° to 50° can meet the needs of ocean applications and the needs of users in other industries. However, the observation shall be carried out at smaller or larger incidence angles for certain applications, for example, for soil moisture observation, the observation effect is better at lower incidence angle, while for geological mapping, geological hazards, and other applications, the observation effect is better at high incidence angle.

7.4.4 Spatial Resolution Design

The spatial resolution of SAR imaging includes azimuth resolution and range resolution. The range resolution is inversely proportional to the radar transmission signal bandwidth. In the SAR system design, setting of different radar transmission signal bandwidths should be considered. Besides, the range resolution is also related to the observed incident angle. Therefore, in the same operating mode, the radar transmission signal bandwidth should be adjusted according to the observed incident angle to obtain the required range resolution. For the strip map mode, the azimuth direction single-look resolution is theoretically half the length of the antenna, and the scan mode can be used to achieve lower resolution; for medium-resolution requirements, the beam width of the extended antenna and strip map imaging can be used. For high resolution, a partial antenna aperture method can be used.

7.4.5 Imaging Swath Design

The imaging swath is mainly related to the coverage of the antenna's range direction beam and the design of the system's wave position. The coverage range of antenna range direction beam can be obtained by weighting the amplitude and phase of each T/R module. Logical design of wave position shall meet the current swath of various observation modes.

7.4.6 Determination of Radiation Resolution

Radiation resolution characterizes the ability of SAR system to distinguish backscattering coefficients of different targets in the imaging range. In the case of large SNR (greater than 10 dB), the radiation resolution can be improved by multi-view

processing, however, the spatial resolution can be reduced at the same time. The formula for calculating radiation resolution is as follows:

$$\gamma_N = 10 \log \left(1 + \frac{1 + \text{SNR}^{-1}}{\sqrt{N}} \right), \quad (7.3)$$

where γ_N is radiation resolution, in dB; SNR is signal-to-noise ratio of image; N is equivalent number of looks.

For monitoring hard target that does not require inversion, the radiation resolution requirements are generally low, and the target monitoring radiation resolution with requirements for inversion are relatively high. In general, SAR images with a radiation resolution better than 2 dB can meet the radiation resolution requirements of most targets.

At present, space-borne SAR systems have various operating modes with different spatial resolution to meet different application requirements. Multi-view processing is an effective method to improve the radiation resolution of SAR image, but the azimuth direction resolution will be degraded. The spatial resolution indicator of high-resolution mode is usually proposed for single look. At this time, although the radiation resolution will be lower, the single-look image resolution can meet the needs because the high-resolution mode is mostly used for hard target observation such as ships. For other resolution modes, the required radiometric resolution can be achieved by multi-look processing.

7.4.7 Radiation Error Source Analysis and Accuracy Determination

Radiation accuracy indicator is an important indicator for quantitative application of SAR image, which refers to the relative error of radiation information. Radiation accuracy reflects the capability of quantitative remote sensing of SAR system, including relative and absolute radiation accuracy.

Relative radiation accuracy refers to the standard deviation of the errors of the backscattering coefficients of known targets in one imaging time, and absolute radiation accuracy refers to the root mean square error between the measured and real values of the backscattering coefficients of targets in different positions of the image.

$$\text{AA} = 10 \log(1 + \varepsilon_{\sigma 0}) + \text{RA}_E, \quad (7.4)$$

where AA is the absolute radiation accuracy, in dB; $\varepsilon_{\sigma 0}$ is the maximum relative error (ratio) for measuring the backscattering coefficient or radar cross section area of the target in two images; RA_E is the external calibration radiation accuracy, in dB.

The error sources affecting the absolute radiation accuracy are analyzed as follows:

1. Beam pointing error of SAR antenna (including pointing error caused by satellite attitude error)

The beam pointing error of SAR antenna includes the beam pointing error caused by various factors (thermal deformation, mechanical change, electrical performance change, etc.) of the antenna itself and the satellite attitude error. The beam pointing error mainly affects the edge part of the observation zone, but has little effect on the middle part of the observation zone. This is because the edge gain of the antenna beam changes rapidly, and the change of beam direction will result in a large difference between the real pattern and the expected one, particularly in the case of the swath edge.

2. Gain error of SAR system

Radiation accuracy is related to the accuracy and stability of the total gain of SAR system (also known as transfer function, including on-board radar equipment and ground imaging processing). The instability error of radar gain is mainly caused by the variation of transmitting power and receiving gain with temperature. After calibrating on-board radar equipment with internal calibration, the gain accuracy of on-board radar equipment is mainly determined by the internal calibration accuracy.

3. Propagation error

The propagation errors of electromagnetic wave include absorption and attenuation of electromagnetic wave by atmosphere and rainfall, scintillation (loss of ionosphere and troposphere), and Faraday effect (polarization rotation of electromagnetic wave caused by ionosphere). Propagation error is uncontrolled, unrelated to SAR system itself, and cannot be solved by SAR. It can only be estimated based on measured data or analysis results. This error is closely related to frequency band and synthetic aperture time.

4. Data processing error

This error is introduced by ground processing, mainly including range direction pulse compression reference function error, azimuth Doppler frequency modulation slope error, and range migration correction algorithm error, etc.

5. Error of external calibration equipment

The error of external calibration equipment is the main factor causing external calibration error. The error of external calibration equipment includes circuit error and stability error of external calibration equipment.

6. Background interference of calibration field

Background interference of calibration field includes multipath interference, ground clutter, and electromagnetic interference of electrical and electronic equipment in

calibration field. Background interference is a factor that affects the accuracy of absolute radiation, so the calibration field must be carefully chosen to reduce its effects.

7. Noise and interference

Noise and interference include thermal noise in the radar receiver, integrated sidelobes of the image, azimuth ambiguity and range ambiguity of the image, and speckle noise of the image.

7.4.8 SAR Calibration Technology

7.4.8.1 Radiation Calibration Technology

Radiation accuracy is closely related to the calibration technology of space-borne SAR. Relative radiation accuracy can be determined by internal calibration method, and absolute radiation accuracy can be determined jointly by internal calibration and external calibration methods.

Internal calibration mainly monitors the change of transmitting power and receiving system gain of SAR system, which is relative calibration. Space-borne SAR payloads can be calibrated by various internal calibration methods:

- (1) Noise calibration: Record the base noise of SAR subsystem;
- (2) Reference calibration: Calibrate the receiving and transmitting channels of central electronic equipment;
- (3) Transmitting calibration of full array: Calibrate the transmitting of phased array antenna;
- (4) Transmitting calibration of a single T/R module: The transmitter of each T/R module on the antenna array is calibrated one by one to test its performance;
- (5) Receiving calibration of full array: Calibrate the reception of phased array antenna;
- (6) Receiving calibration of a single T/R module: The receiving part of each T/R module on the antenna array is calibrated one by one to test its performance.

In practical work on orbit, the internal calibration mode can be flexibly selected, usually with noise, reference, full array transmitting and receiving calibration. When T/R components need to be fully tested, transmitting and receiving calibration is carried out on a single T/R component. In addition, it can be calibrated without imaging during on-orbit testing, that is, continuous calibration is performed to continuously monitor system changes after a boot-up.

The ultimate goal of space-borne SAR detection is to obtain the absolute radar cross-sectional area of the ground objects. By the easily implemented internal calibration method in combination with the external calibration method, the corresponding relationship between the gray-scale value of radar image and the absolute radar cross section area by observing the known radar cross section area to eliminate error of the

SAR system can be obtained, and the backscattering characteristics of the observed target can be accurately determined to realize absolute calibration. The external calibration method is difficult to implement, and requires a wide calibration field and a large number of calibration sources that accurately measure the radar cross-sectional area. The electromagnetic environment of the calibration field should be very “clean”, so that the ground clutter generated by the calibration field does not interfere with the RCS of the standard reflector.

7.4.8.2 Geometric Calibration Technology

The absolute offset of the azimuth and range directions of the SAR geometric calibration measurement system (geometric scaling constant) is very crucial for the mapping areas without ground control points. In most cases (such as oceans, desert areas), ground control points are not available or difficult to identify.

The measurement of geometric calibration constants depends on the calibrator set in the calibration field as the reference point target. The geographic position of the reference target can be accurately determined by GPS signals. The image coordinates of the reference target are practically measured from the image and compared with the standard reference coordinates to measure the position offset of the azimuth and the range directions.

The peak position of reference target impulse response is measured from the calibration field image as its image coordinate, and interpolation shall be performed to remove the influence on discrete data. For example, assume that the image coordinates are R in the range direction and X in the azimuth direction, then the range geometric offset $\Delta R = R - R_0$ and the azimuth geometric offset $\Delta X = X - X_0$, where (R_0, X_0) are the reference image coordinate. In order to improve the measurement accuracy, at least three reference point target statistical measurements are required, so

$$\Delta R = \frac{1}{n} \sum \Delta R_i, \quad (7.5)$$

$$\Delta X = \frac{1}{n} \sum \Delta X_i, \quad (7.6)$$

where X_i is the position coordinate of the i th reference point in the azimuth direction, and R_i is the geometric offset of the i th reference point in the range direction.

7.4.9 Analysis of Impulse Response Characteristics

The description of impulse response characteristics is mainly based on peak sidelobe ratio and integral sidelobe ratio. Peak sidelobe ratio indicator describes the system's ability to eliminate distortion caused by adjacent point targets, and integral sidelobe

ratio indicator describes the system's ability to eliminate distortion caused by adjacent distributed targets.

7.4.9.1 Peak Sidelobe Ratio

Peak Sidelobe Ratio (PSR) refers to the ratio of peak of the highest sidelobe to peak of the main lobe in point target impulse response, which reflects the system's ability to detect dim small targets. Generally, it is measured in dB.

$$\text{PSLR} = 10 \lg \frac{P_{s\max}}{P_m}, \quad (7.7)$$

where $P_{s\max}$ is peak of the highest sidelobe in the impulse response, and P_m is the peak of main lobe in the impulse response.

7.4.9.2 Integral Sidelobe Ratio

Integral sidelobe ratio refers to the ratio of sidelobe energy to main lobe energy in the point target impulse response, which indicates the extent to which the dark area is "submerged" by bright area signals. Generally, it is measured in dB.

$$\text{ISLR} = 10 \lg \frac{E_s}{E_m}, \quad (7.8)$$

where E_s and E_m are the sidelobe energy and the main lobe energy in the Impulse Response Function (IRF), respectively.

7.4.10 System Sensitivity Analysis

Noise equivalent backscattering coefficient ($\text{NE}\sigma^0$) represents the sensitivity of SAR imaging system, reflects the lower limit of backscattering coefficient that the system can image, and is a key indicator to measure the ability of the system to detect weak signals. If the backscattering coefficient of the target is less than the scattering coefficient, the reflected energy of the target will be lower than the system noise, and the SAR system cannot effectively detect the existence of the target.

Space-borne SAR $\text{NE}\sigma^0$ is related to transmission power (P_{av}), antenna transmission gain (G), satellite-to-ground distance (R), range direction resolution (P), and transmission wavelength, etc. For multi-polarized SAR satellites, satellite-to-ground distance, SAR transmission wavelength, and range resolution have been determined, so system sensitivity can be improved in terms of both transmit power and antenna transmit gain.

Satellite-borne SAR missions have two requirements for system sensitivity: for the target surveillance with high spatial resolution (less than 10 m), such as ship surveillance, offshore oil platform surveillance, and iceberg surveillance, it is generally only necessary to see the presence of targets directly from the image that has not very high requirement on system sensitivity, generally up to -16 dB; for the monitored ocean and land target with weak reflection as well as medium and low spatial resolution, the interested ocean and land information is usually obtained by inversion. At this time, the system sensitivity requirements are higher, usually up to -24 dB.

7.4.11 Ambiguity Analysis

Ambiguous signal refers to a signal formed by aliasing other nonhuman interference signals outside the imaging area after being imaged and processed with useful signals in the imaging area, which seriously generates false targets. The criterion of the system's ambiguity interference degree is the ambiguity ratio, which is defined as the ratio of the total power of the echo signal to the total power of the echo signal in the mapping band. Ambiguity problems can be divided into azimuth ambiguity and range ambiguity. Azimuth ambiguity is caused by the Doppler spectrum folding caused by the difference between the Doppler frequency of the target echo in some angles and the Doppler frequency of the main beam, which is an integral multiple of the pulse repetition frequency. Range ambiguity is caused by the existent antenna sidelobes, by which echoes from the ambiguous region enter the radar receiver through the antenna sidelobes.

Generally, the azimuth ambiguity ratio of space-borne SAR system is less than -16 dB and the range ambiguity ratio is less than -18 dB. For ocean applications, the reflected echo is very weak and needs a high ambiguity ratio. Generally, the azimuth ambiguity ratio is less than -18 dB, and the range ambiguity ratio is less than -20 dB.

7.4.12 Selection of Payload High-Speed Real-Time Compression Method and Compression Strategy

Different from SAR image, optical image, or video data, space-borne SAR payload raw data is a discrete memoryless source, which cannot be compressed by using the correlation between the data. Instead, the original signal is compressed at a high bit rate in real time under the assumption that the SAR raw signal data has a zero mean Gaussian distribution signal with a slowly varying variance in both the range direction and the azimuth direction.

Space-borne SAR data rate is determined by PRF of SAR system, sampling number and quantization bits of each sampling point, and usually reduced by data compression. At present, Block Adaptive Quantization (BAQ) compression is widely used in satellites worldwide. The compression ratio of 8:3 or 8:4 can be selected to meet the data transmission requirements.

7.4.13 Beam Pointing Accuracy Control

The imaging quality of spaceborne SAR is required to be high, and the accuracy of SAR antenna beam pointing is a key factor affecting the acquisition of high-quality to-ground remote sensing data by space-borne SAR payload. Doppler parameter (including Doppler center and Doppler rate) errors will be caused by beam azimuth direction pointing error. Beam range direction pointing error will affect the echo gain of the scene target, and even cause the range-directed beam to deviate from the original imaging area, resulting in range ambiguity, sensitivity, and radiation accuracy decline. The beam pointing accuracy (error) and influence of SAR antenna are shown in Fig. 7.2.

The pointing accuracy in the azimuth direction mainly affects the Doppler center frequency of SAR antenna and the aiming accuracy in the azimuth direction of beaming. The pointing accuracy in the range direction mainly affects the range ambiguity of image, system sensitivity, and radiation accuracy.

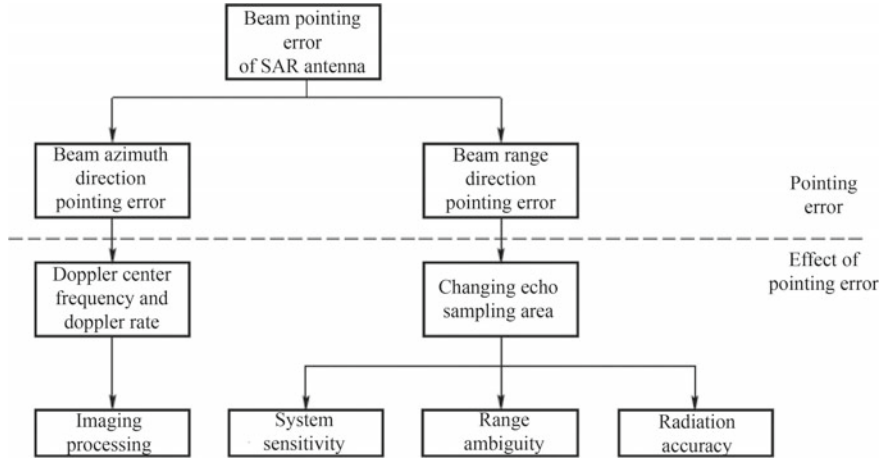


Fig. 7.2 SAR antenna beam pointing error decomposition and its influence

7.4.14 High-Precision Yaw Guidance Control of Satellite Attitude

For space-borne SAR, the Doppler characteristic is the main factor determining the azimuth performance of the radar, and directly affects radar azimuth direction resolution, PRF selection, azimuth ambiguity, and final image processing accuracy. The inaccurate Doppler center frequency will reduce the SNR, increase the azimuth ambiguity, and shift the position of the output image, thus affecting the image positioning.

Due to the high velocity of satellite, the Doppler center usually reaches the level of kHz, which requires a larger PRF. The compromise between azimuth ambiguity and range ambiguity is very significant. Due to the Earth rotation and satellite attitude error, the Doppler echo characteristics are more complicated, so the incorrect estimation of Doppler center frequency and Doppler frequency rate will affect the accuracy of final image processing. In order to compensate for Doppler center offset, in addition to various estimation methods for Doppler center of echo signal, this can be avoided using satellite attitude guidance method in the data acquisition stage.

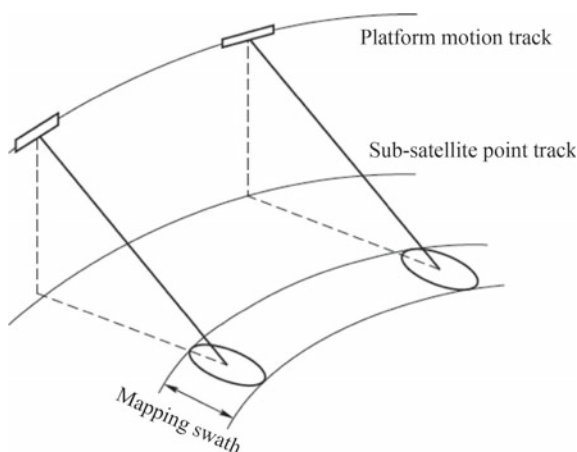
Yaw guidance technology is based on this concept. The so-called yaw guidance is to pre-maneuver a yaw angle of the satellite through attitude control to compensate for the deviation of the Doppler center caused by the rotation of the Earth and make the Doppler center of the echo approach zero. In order to further reduce the Doppler center frequency, a new two-dimensional guidance technique, Total Zero Doppler Steering (TZDS), has been proposed on the basis of yaw guidance, two-dimensional guidance technology in recent years.

When the center of the SAR antenna beam is perpendicular to the Earth's surface target illuminated by the track, the Doppler center frequency will deviate from zero because the velocity vector between the beam center ray (or pointing) and the target is no longer perpendicular to the satellite due to the influence of the Earth rotation. This means that the range direction and azimuth direction data of SAR echo signal will produce two-dimensional coupling, which increases the difficulty of imaging processing.

7.5 Design of Space-Borne SAR Imaging Mode

SAR imaging modes generally include strip, scan, and spotlight, which may be different for specific implementation, but they are all adaptive variations based on these three modes. At present, the main derived modes include Slide-spot, DPC, TOPSAR, Mosaic, Wave mode, etc. The specific imaging mode is decided according to user requirements. In addition, on-orbit specific working mode can be programmed and combined according to user requirements.

Fig. 7.3 Schematic diagram of strip mode



7.5.1 Strip Mode

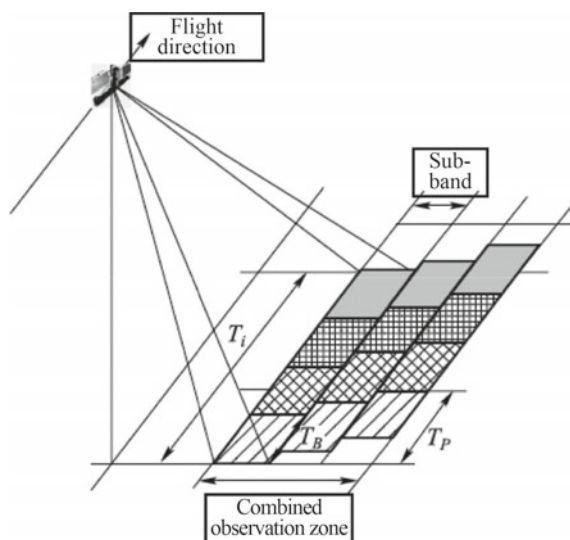
Strip mode is the most basic work mode of SAR, as shown in Fig. 7.3, under which the antenna beam center pointing remains unchanged. With the movement of the platform, the beam sweeps across a strip area on the ground, which is called mapping swath. The image obtained in this mode is continuous in azimuth direction, and the length of mapping swath depends on the distance of motion during SAR operation.

7.5.2 Scan Mode

In civil areas such as disaster prevention and mitigation, it is necessary to obtain large-scale surveying and mapping information efficiently. Because of the limitation of pulse repetition frequency and range direction ambiguity, the common strip working mode cannot obtain the surface image of wide surveying and mapping swath. The concept of scanning mode breaks through this limitation and increases the bandwidth of distance mapping at the cost of reducing azimuth direction resolution, as shown in Fig. 7.4.

For Scan SAR system, it is required that antennas have one-dimensional agility on beam pointing. When SAR works in scanning mode, the radar antenna first transmits a series of pulses along one beam pointing and receives corresponding echoes. Changing the direction of the antenna in the range direction, the beam jumps to another direction and continues to illuminate. Each beam pointing to the corresponding illumination band is called “sub-observation band” or “sub-band”. Finally, wide-angle beam scanning in the range direction is realized by phase control.

Fig. 7.4 Sketch of scanning mode



7.5.3 Spotlight Mode

In the spotlight mode, the beam must always illuminate the target area with the higher control level of the target pointing during the operating time. Spotlight mode data can be processed in different ways to achieve different applications, including high- and medium-resolution modes. High-resolution mode achieves high resolution by long-time accumulation, such as 0.5–2.0 m or higher; medium-resolution mode divides long-time data into multiple short synthetic aperture time data in azimuth time domain to obtain multiple medium-resolution images.

7.6 Scheme Description of Space-Borne SAR Payload System

The SAR payload is the core system of SAR satellites on-orbit dynamic imaging. It is made up of antennas and central electronic devices. It can also be divided into transmitting channels and receiving channels according to the function. The main function of the SAR payload is to generate a signal source, transmit the signal to the transmitting antenna through the RF system, and then radiate the signal to the designated area through the antenna array. The antenna receives, amplifies, converts, and demodulates the echo signal simultaneously and converts it into a digital signal and transmits it to the ground processing system to provide raw data for subsequent imaging processing.

7.6.1 System Configuration and Its Topology

Space-borne SAR payload subsystem is composed of data processor, transmitter, transmitting front-end, deployable large-scale transceiver antenna, receiving front-end, receiver, frequency source, and other single machines and subsystems, as shown in Fig. 7.5. In the injection, most SAR antennas are folded and compacted. After the satellite enters its operational orbit, the antenna is unlocked and deployed, and the subsystem equipment is powered up and started up.

The SAR electronic equipment in the SAR subsystem cabin is mainly responsible for the control of power-on/off of single machine for SAR, switching between primary and backup devices, the monitoring and control of the system, the communication with satellite platforms, the generation of SAR reference frequency, timing signal, linear frequency modulation signal, the reception of radar echoes, data acquisition, processing, compression and packaging, data stream forming and sending to the data transmission subsystem, and performing monitoring and internal calibration together with the SAR antenna subsystem.

The main function of the SAR antenna subsystem is to distribute the radio frequency signal provided by the SAR electronic equipment to each T/R module through the feed network in the transmitting state, modulate the amplitude and phase of the signal by the T/R module according to the beam scanning instruction, and radiate the output signal by the antenna radiation array with H polarization or V polarization oriented to the specified direction; in the receiving state, the echo signal received by the array is phase shifted and amplified by the receiving branch of the T/R module, and sent to the radar receiver through the feed network.

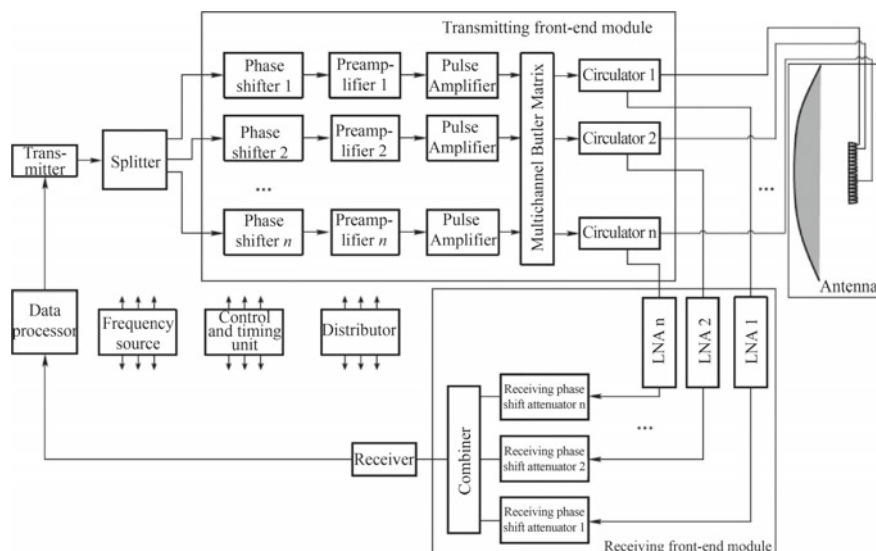


Fig. 7.5 SAR payload topology

7.6.2 System Function Design

When on-orbit space-borne SAR operates, the electronic equipment subsystem generally has the working modes of spotlight mode, strip mode, and scan mode. According to the requirements of resolution and width, the observation area can be observed. Besides, it has the function of internal calibration, completing the calibration of electronic equipment and antenna array of SAR system, realizing the system chain. Correction of path error can improve the accuracy of quantitative processing. In addition, the system also has the compression function of SAR observation data to reduce the data transmission pressure of satellite-ground data transmission link.

7.6.3 System Design Constraints

7.6.3.1 Task-Level Design Constraints

The orbit of the space-borne SAR system is analyzed according to the requirements on orbital design of satellite observation area and revisits period in general requirements for development. At present, the solar synchronous regression frozen orbit is mostly chosen for satellite-borne SAR, which can provide stable illumination conditions to ensure the minimum change of the incident angle of sunlight on the orbital plane, while the eccentricity and perigee angle of the frozen orbit will remain unchanged during the operation of satellite, so as to ensure that the altitude change of the satellite passing through the same area changes as small as possible, which is beneficial to the image quality of SAR payload.

Unlike visible spectral satellite, SAR satellite orbit usually chooses solar synchronous orbit, whose payload imaging with the very high power consumption does not depend on the illumination condition of the ground. Based on the above considerations, the orbits between local times of descending node 5:00–7:00 or 17:00–19:00 are generally chosen, and the orbital altitudes of LEO SAR satellites are generally in the range of 450–1100 km. According to the typical application requirements of GF-3 satellite, SAR satellites with resolution of 1 m@ swath 10 km ~ resolution of 10 m@ swath 100 km in C band (5.4 GHz) are used to observe Earth through the right- and left-side looking by satellite attitude maneuver, so as to expand the observation range. The conventional incidence angle is 20°–50° and the extended incidence angle is 10°–20° or 50°–60°. In case of unilateral view, the average period of revisit is less than three days; in case of bilateral view, under the mode of 10 m resolution and 100 km mapping swath, the revisit period in 90% of the observable areas is less than 1.5 days.

In order to ensure the quality of SAR on-orbit imaging, it is generally required that the attitude pointing accuracy is better than 0.03° (three-axis, 3σ), the attitude stability is better than $1 \times 10^{-3}/s$ (three-axis, 3σ), and the ability of side swing (rolling) should be available. The normal on-orbit flying attitude is in the right-side

looking, which can be maneuvered from the right-side looking to the left-side looking through the roll-side swing of the whole satellite.

Satellite design on-orbit service life should be more than eight years; the daily operating frequency of satellite should be more than 28.

7.6.3.2 Design Constraints for Large-Scale Engineering Systems

The relative and absolute radiation accuracy of SAR single image should be better than 1.0 and 2.0 dB, so as to ensure the ground inversion accuracy and quantitative application effect of space-borne SAR data. The auxiliary data broadcasted by on-board bus is received by SAR payload, arranged with SAR raw data uniformly, and sent to the ground application system.

During the period of satellite launching and on-orbit lifetime, it is necessary to provide a good thermal environment for SAR antenna to ensure the reliability of instruments and equipment. The temperature of SAR antenna and waveguide slot should be -20°C to $+45^{\circ}\text{C}$ and -50°C to $+60^{\circ}\text{C}$, respectively.

7.6.3.3 Satellite General Design Constraints

In order to ensure the on-orbit performance, reliability of SAR payload, and the interface matching between subsystems, constraints on SAR payload design are proposed for satellite system.

In order to ensure the matching between SAR payload and other space-borne subsystems, the mass of SAR subsystem is required to be not more than 1120 kg, in which the mass of antenna subsystem is not more than 1060 kg, the mass of central electronic subsystem is not more than 60 kg, and the power consumption should be less than 8000 W.

Considering the data transmission rate, SAR payload data is required to be compressed with large compression ratio. However, the SAR payload imaging quality is sensitive to large compression ratio, and the loss of SNR is large. Compression is generally performed at the ratio of 8:4 or 8:3.

7.6.4 Scheme Description of SAR Payload Electronic System

7.6.4.1 Central Electronic Equipment

Central electronic equipment mainly consists of monitoring timer, reference frequency source, FM signal source, receiving switch matrix, radar receiver, data generator, internal calibrator, radar distributor, and high-frequency cable network.

7.6.4.2 Antenna Subsystem

The antenna subsystem consists of waveguide slot antenna sub-array, T/R module, delay amplifier module, wave control computer and wave control unit, radio frequency transceiver and calibration feed network, secondary power supply, antenna distributor, high- and low-frequency cable network, active installation board, structure frame, deployment mechanism, and thermal controller.

7.6.5 Description of SAR Antenna System Design

SAR antenna includes three components: antenna array, antenna deployment mechanism, and antenna thermal control.

7.6.5.1 Design of SAR Antenna Array

When the SAR antenna array is in the state of signal transmission, the RF signal provided by the driving amplifier is distributed to each T/R module through the feed network. The amplitude and phase of the signal are modulated by the T/R module according to the beam scanning instructions. The output signal of the SAR antenna array is radiated from the antenna radiation array to the designated airspace. When the SAR antenna array is in the signal receiving state, the echo signal received by the array is phase shifted and amplified by the receiving branch of the T/R component, and sent to the receiver via the feed network; together with the central electronic device, polarization internal calibration task of SAR subsystem is completed.

SAR antenna array is a C-band multi-polarized two-dimensional planar active phased array antenna, which consists of dual-polarized waveguide slot antenna, T/R module, delay amplifier module, wave control unit, array secondary power supply, feed network and cable, active mounting plate, and structure frame. The specific composition and definition of SAR antenna array are shown in Fig. 7.6.

The SAR antenna is unlocked and deployed after the satellite is on orbit. When the antenna is in the transmitting state, the RF signal emitted by FM signal source is amplified by driving amplifier, and distributed to each T/R module by feeding network after delay amplification. According to the beam control instructions, the phase control is adjusted by each T/R module, and the output signal is radiated by the antenna radiation array toward the designated airspace. When the antenna is in the receiving state, the echo signal in the specified space is received by the array after the phase shift performed by the receiving branch of the T/R module. After being synthesized by the feed network, the signal is sent to the radar receiver through the combination of the driving amplifier and the microwave product.

SAR antenna uses a single unit with telecommunication functions (including radio frequency transceiver, power supply, control related single unit, etc.) to realize the single polarization, dual polarization, and four polarization modes combined

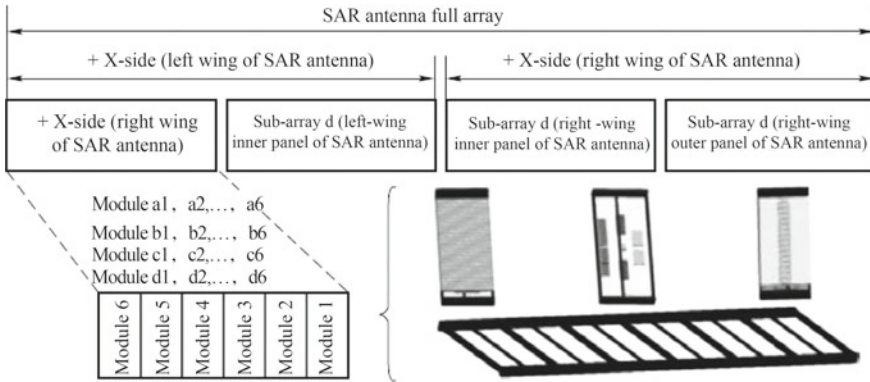


Fig. 7.6 Sketch of SAR antenna array composition of satellite GF-3

by H polarization and V polarization. Therefore, for the radio frequency link, H polarization and V polarization are completely identical.

7.6.5.2 SAR Antenna Deployment Mechanism

The deployment mechanism of SAR antenna is mainly composed of deployment controller, +X side deployable support truss, and -X side deployable support truss, which can realize the functions of unlocking, deployment control, and deployable locking support for SAR antenna connection. The specific operation process is as follows:

- The -X-wing SAR antenna and the +X-wing SAR antenna are reliably pressed against the satellite side wall by the compress and release mechanism to withstand and transmit the mechanical load of the active segment of the satellite launch;
- Under the action of the satellite system circuit, the compress and hold-down and release device performs release operation to reliably release the constraints on SAR antenna;
- According to the received command of the TT&C subsystem, the start-up and stop, deployment, and folding of the SAR antenna deployment are performed by controlling the start-up and stop, forward rotation, and reverse rotation of the motor (reversing (folding) operation only in the case of ground test and fault conditions);
- Monitor the working state of the SAR antenna deployment mechanism, and transmit the telemetry data to the ground through the data transmission subsystem.
- According to the predefined criterion, the deployment mechanism is independently shut down when the antenna is deployed in place, and stops the antenna deployment or folding action independently or according to the instructions under abnormal circumstances.

- During the satellite lifetime, the SAR antenna can be reliably supported with certain stiffness, intensity, and accuracy, and meets the requirements of attitude control and imaging accuracy.

As the support structure of the planar antenna board, the deployable support truss is directly related to the positional accuracy, profile precision, and fundamental frequency of the antenna array after it is unfolded and locked on orbit, which is mainly composed of a satellite body support frame, an inner frame assembly, an outer frame assembly, a truss bar, a support bar assembly, a 90° hinge, and a 180° hinge.

7.6.5.3 SAR Antenna Thermal Control

SAR antenna thermal control system is designed to provide a good thermal environment for antenna instruments and equipment during satellite launching and on-orbit lifetime, so as to ensure the reliability of instruments and equipment. The temperature requirement of single SAR antenna is $-20\text{ }^{\circ}\text{C} \sim +45\text{ }^{\circ}\text{C}$, and that of waveguide slot is $-50\text{ }^{\circ}\text{C} \sim +60\text{ }^{\circ}\text{C}$; the temperature gradient in the single module is less than $7\text{ }^{\circ}\text{C}$, and that in the full array is less than $10\text{ }^{\circ}\text{C}$.

The SAR antenna is characterized by many working modes, high heat consumption, large heat loss, and high-level SAR antenna design specification. The temperature uniformity of T/R module and delay module is required when SAR antenna works. According to the requirement of load subsystem, the temperature gradient in a single module (T/R module and delay amplifier module) is less than $7\text{ }^{\circ}\text{C}$ and that in the full array (T/R module and delay amplifier module) is less than $10\text{ }^{\circ}\text{C}$. In order to dissipate the temperature of T/R module with concentrated heat consumption, the embedded heat pipe network is attached on each SAR antenna mounting plate to maintain the temperature uniformity of the mounting plate and the equipment on it.

7.7 Analysis and Design of Space-Borne SAR Imaging Quality

In SAR high-resolution imaging mode, satellite beams or platforms oscillate according to certain rules to form spotlight imaging. In this dynamic adjustment, non-ideal factors such as satellite platform error, satellite velocity error, orbit perturbation, attitude error, and attitude stability will affect the imaging quality. Therefore, this section focuses on the quality analysis and design method of on-orbit dynamic imaging.

7.7.1 Satellite Position Measurement Error

The influence of satellite position measurement error mainly refers to the change of slant distance during the synthetic aperture time. Therefore, the influence of satellite position measurement error on space-borne SAR imaging can be analyzed according to the slant distance error. The slant distance error introduced by satellite position measurement error can be expanded into slant distance constant term, primary term, quadratic term, cubic term, and high-order term. Among them, the constant term in the slant distance error will cause the offset in range of the target imaging position, the primary term will cause the offset in azimuth of the target imaging position, the quadratic term will cause the main lobe widening, the deterioration of the peak sidelobe ratio and the integral sidelobe ratio of the target, and the cubic term will mainly cause the asymmetry of the sidelobe of the target.

The constant term in the orbit error component will lead to the geometric positioning error of SAR image, but its influence on the imaging can be neglected. The target azimuth positioning error caused by satellite position measurement error is given by the following formula:

$$\Delta T_{az} = \Delta T_x + \Delta T_z, \quad (7.9)$$

where ΔT_{az} represents the positioning error of SAR image along the target azimuth direction, ΔT_x represents the positioning error of target azimuth caused by the error of satellite position along the course, and ΔT_z represents the positioning error of target azimuth caused by the error of satellite position along the H direction of altitude. ΔT_x and ΔT_z are given by Formula (7.10):

$$\begin{aligned} \Delta T_x &= \frac{\Delta R_x R_t}{R_s}, \\ \Delta T_z &= \frac{RV_g V_e}{V_r^2} (\cos \xi_t \sin \alpha_i \cos \theta) \Delta \theta, \end{aligned} \quad (7.10)$$

where ΔR_x is the error of satellite position along the course, R_t is the distance from the target to the Earth's center, R_s is the distance from the satellite to the Earth's center, V_g is the Earth's velocity, V_r is the equivalent velocity, ξ_t is the target geocentric latitude, α_i is the inclination angle of orbit, θ is the lower angle of view of the beam center, and $\Delta \theta$ is the angle of view change caused by satellite altitude error. $\Delta \theta$ is given by Formula (7.11):

$$\Delta \theta = \arccos \left[\frac{R^2 + R_s^2 - R_t^2}{2R_s R} \right] - \arccos \left[\frac{R^2 + (R_s + \Delta R_z)^2 - R_t^2}{2(R_s + \Delta R_z) R} \right]. \quad (7.11)$$

The influence of satellite position measurement error on positioning errors in range of targets in SAR images is given by the following formula:

$$\Delta T_{rg} = \frac{\Delta R_y R_t}{R_s} + \frac{R \Delta \theta}{\sin \eta}, \quad (7.12)$$

where ΔT_{rg} represents the target positioning error in range direction caused by the satellite position measurement error, ΔR_y represents the satellite position measurement error perpendicular to course, and η represents the incident angle.

The Doppler center estimation error caused by the satellite velocity measurement error is given by

$$\Delta k_d = \frac{\|\vec{v}_{s0}\|^2}{2\|\vec{r}_{s0} - \vec{r}_g\|} - \frac{\left[(\vec{v}_{s0})(\vec{r}_{s0} - \vec{r}_g)^T\right]^2}{2\|\vec{r}_{s0} - \vec{r}_g\|^3} - \frac{\|\vec{v}_{s0} + \Delta\vec{v}\|^2}{2\|\vec{r}_{s0} - \vec{r}_g\|} - \frac{\left[(\vec{v}_{s0} + \Delta\vec{v})(\vec{r}_{s0} - \vec{r}_g)^T\right]^2}{2\|\vec{r}_{s0} - \vec{r}_g\|^3}, \quad (7.13)$$

where Δk_d represents Doppler center estimation error caused by satellite velocity measurement error, in Hz.

7.7.2 Satellite Orbit Perturbation

The satellite orbit is basically an elliptical orbit, which is determined by the gravitational field of the Earth's center. But the Earth's gravitational field is not a complete central gravitational field. In fact, the Earth is not spherically symmetrical, and such non-centrality will produce a perturbation effect on satellite orbit. Orbital perturbation mainly affects the mapping swath and target intensity of SAR images, which in turn affects the radiation quality indicators of SAR images.

7.7.3 Satellite Attitude Error

Satellite attitude includes yaw, pitch, and roll. Satellite attitude error includes satellite attitude control error and satellite attitude measurement error.

7.7.3.1 Satellite Attitude Control Error

Satellite attitude control error refers to the error of satellite attitude control deviating from the preset state. The satellite attitude control error will cause the radar beam to deviate from the pre-specified scenario. In the absence of the satellite attitude measurement error, the real radar beam pointing can be obtained by measurement.

The satellite attitude control error will not cause the estimation error of Doppler parameters, but will affect the imaging quality indicators such as target intensity and imaging swath in scenario.

7.7.3.2 Satellite Attitude Measurement Error

The error of satellite attitude measurement is caused by the inaccuracy of satellite attitude measurement. Satellite attitude measurement errors will lead to orbit-based Doppler center estimation errors and azimuth frequency estimation errors, which will affect the imaging quality of space-borne SAR.

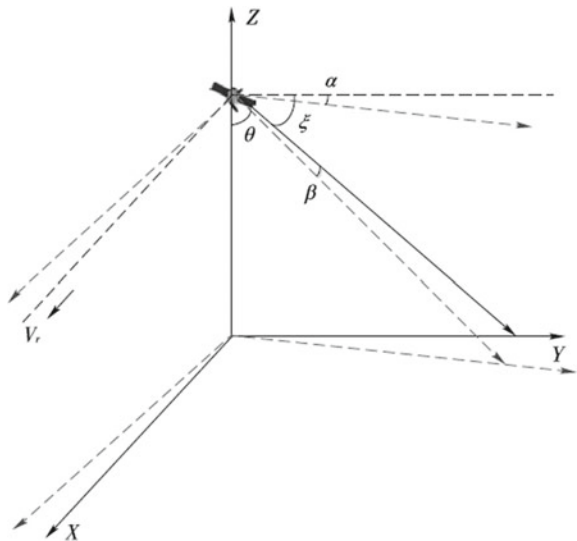
(1) Satellite yaw error

The simplified geometric relationship of space-borne SAR imaging by satellite in yaw is shown in Fig. 7.7. The platform yaw will cause the radar beam to rotate around the Z-axis, and the trajectory of the ground illumination curve is approximately a circle. Radar works in the side-looking mode. The center of the radar beam is perpendicular to the radar course. The real line represents the ideal radar operating coordinate system, and the dotted line represents the radar operating coordinate system in the presence of platform yaw error.

The orbit-based Doppler center estimation error caused by the yaw angle of the satellite platform is given by the following formula:

$$\Delta f_{dc}^{(\alpha)} \approx -\frac{2V_r \sin \beta}{\lambda}, \quad (7.14)$$

Fig. 7.7 SAR imaging geometric relation with yaw angle α



where $\Delta f_{dc}^{(a)}$ represents Doppler center estimation error caused by platform yaw angle α , in Hz; V_r represents the satellite equivalent speed, in m/s; λ represents the wavelength corresponding to the center frequency of the transmitting signal, in m; β represents the angle at which the beam center is offset in the slanted plane of the image, in ($^\circ$), and is given as the following:

$$\cos \beta = \sin^2 \xi + \cos^2 \xi \cos \alpha, \quad (7.15)$$

where $\xi = 90^\circ - \theta$, θ is beam center lower view angle.

(2) Satellite pitch error

The platform pitch makes the centerline of the radar beam rotate around the Y -axis. If the pitch measurement error of the platform is set to be α ($^\circ$) and the angle of the beam center offset on the imaging oblique plane to be β ($^\circ$), the orbit-based Doppler center estimation error caused by the pitch of the satellite platform is approximately given by the following equation:

$$\Delta f_{dc}^{(\alpha)} \approx -\frac{2V_r \sin \beta}{\lambda}. \quad (7.16)$$

The relationship between β and α is given by the following equation:

$$\cos \beta = \sin^2 \theta + \cos^2 \theta \cos \alpha, \quad (7.17)$$

where θ represents beam center lower view angle.

(3) Satellite roll error

The satellite roll causes the radar beam to rotate around the X -axis. When the beam azimuth is 0° , there is no influence on the Doppler center and azimuth frequency estimation. However, satellite platform roll will cause the radar transmit beam to move in the range direction, which is equivalent to weighting the generated pulse and affecting the antenna gain. For example, in ideal situation, the target at the center of the scenario is no longer at the center of the scenario after the radar platform has been rolled, and its echo energy will decrease, but its distance to the radar will not change, so do the Doppler frequency and the azimuth frequency of the response. If the roll is serious, it may cause the range beam to deviate from the original imaging area.

7.7.4 Satellite Attitude Stability

Attitude errors will cause beam pointing error. Stability is an indicator to measure the stability of satellite platform. It is usually defined as three times root mean square

value of antenna pointing rate in the synthetic aperture time. Usually, assuming that the change of attitude angle generally satisfies the sinusoidal variation, that is

$$\theta(t) = A \sin(\omega_0 t) + \theta_0, \quad (7.18)$$

$$\sigma_{\text{ant}} = \frac{3}{T_s} \sqrt{\int_0^{T_s} \left(\frac{d\theta(t)}{dt} \right)^2 dt} = 3A\omega_0 \sqrt{\frac{1}{2} \left(1 + \frac{\sin 2\omega_0 T_s}{2\omega_0 T_s} \right)}, \quad (7.19)$$

where A represents the amplitude of attitude angle change, ω_0 represents the angular frequency of attitude angle change, θ_0 represents the initial value of attitude angle, $\theta(t)$ is the attitude angle, σ_{ant} is the attitude stability, and T_s is the synthetic aperture time.

The influence of satellite attitude instability on imaging quality is reflected in two aspects: one is to modulate the amplitude of the echo signal to produce paired echoes; the other is to cause small changes in the Doppler spectrum, resulting in errors in the estimated Doppler center frequency. At present, the attitude stability of SAR system can reach $10^{-4}^\circ/\text{s}$. For high-resolution SAR satellites, the attitude stability has little influence on image quality when it reaches $3 \times 10^{-3}^\circ/\text{s}$, so the engineering requirement of attitude stability is $1 \times 10^{-3}^\circ/\text{s}$. Therefore, it can be seen from the analysis of the influence of the attitude error of the previous satellite on the SAR imaging quality that the attitude stability has little effect on the SAR imaging quality.

7.7.5 Ground Resolution

Ground resolution is a quantitative expression of ability of SAR to distinguish ground adjacent point targets, which is determined by the half power main lobe width of point target impulse response. The ground resolution of SAR system includes range resolution and azimuth resolution. The range resolution depends on the incident angle and the system bandwidth; the azimuth resolution depends on the antenna beam width in azimuth direction.

7.7.5.1 Range Resolution

The SAR system has provided 11 signal bandwidths for the 12 imaging modes of the GF-3 satellite and its resolution application requirements. It can be seen from Table 7.3 that the designed signal bandwidth can be adjusted from 10 to 240 MHz, and the imaging requirements are met in each imaging mode. In general, the higher the resolution is, the larger the required signal bandwidth; at the same resolution, the smaller the angle of incidence is, the greater the required signal bandwidth.

Table 7.3 Signal bandwidth and range resolution for different imaging modes

Imaging mode		Resolution range/m	Design result	
			Signal bandwidth/MHz	Resolution range/m
Spotlight mode		0.9–2.5	240	0.98–2.29
Hyperfine strip map mode		2.5–5	120/100	2.33–4.44
Fine strip map mode		4–6	100/60	3.42–5.88
Standard strip map mode		15–30	50/40/20	12.78–26.77
Wide scan mode		50–110	30/20/10	51.11–103.35
Full polarization strip mode		6–9	60/40/30	5.34–8.88
Wave mode		8–12	100/60/50	6.43–10.87
Global observation mode		350–700	2	329.61–674.79
Extension	Low incidence angle	15–30	80	12.26–25.38
	High incidence angle	20–30	20	20.07–23.57

7.7.5.2 Azimuth Resolution

The azimuth resolution of SAR mainly depends on the length of antenna in the azimuth direction or the equivalent beam width of transmitting and receiving. Table 7.4 gives the resolution indicator requirements for each imaging mode, the design values of antenna transmitting and receiving beam width, and the design values of resolution and the indicator compliance. Generally, the higher the resolution is, the larger the required azimuth direction beam width is, but it has little to do with the incident angle.

7.7.6 Peak Sidelobe Ratio and Integral Sidelobe Ratio

Peak sidelobe ratio and integral sidelobe ratio mainly depend on amplitude and phase error control and processing weights. In the following sections, the weighting suggestions of satellite azimuth and range direction azimuth amplitude and phase errors and ground processing are given, as well as the sidelobe performance of each mode under the above error allocation values and weighting functions.

7.7.6.1 Error Control

(1) The amplitude and phase error control in the azimuth direction

The main factors affecting the azimuth direction amplitude and phase errors are the gain stability of the receiving channel, the short-term stability of the frequency

Table 7.4 Design beam width and design resolution for antenna transmission and reception for different imaging modes

	Resolution range/m	Azimuth direction designed beam width/(°)		Resolution/m
		Transmitted beam width	Received beam width	
Spotlight mode	1.0–1.5	0.4, scan ± 1.9	0.4, scan ± 1.9	1.0–1.5
Hyperfine strip map mode	3	0.436	0.752	3
Fine strip map mode	5	0.32	0.32	5
Standard strip map mode	25	0.188	0.188	25
Wide scan mode	100			100
Full polarization strip mode	8		0.197	8
Wave mode	10			10
Global observation mode	500		0.188	500
Extension of the incidence angle	25			25

source, PRF jitter, and the attitude stability of the satellite. In addition, the Doppler parameter estimation accuracy of ground processing will also introduce amplitude and phase errors. Table 7.5 gives the azimuth direction error distribution.

The satellite attitude instability will lead to errors in paired echoes and Doppler center frequency. The simulation analysis of high-resolution space-borne SAR shows that the attitude stability has little influence on the image quality when it reaches $3 \times 10^{-3}^{\circ}/s$. From the engineering point of view, the attitude stability can reach $1 \times 10^{-3}^{\circ}/s$.

(2) The amplitude and phase error control in the range direction

Table 7.5 Amplitude and phase error distribution in the azimuth direction in SAR imaging

Error source	Error allocation value
Amplitude/dB	First-order error/quadratic error 0.2
Frequency source short-term stability/[$(^{\circ}) (10\text{ ms})^{-1}$]	1×10^{-10}
Gain stability of receiving channel/dB	$\leq \pm 0.5$
PRF jitter/ns	2
Fdc estimation error/Hz	30
Fdr estimation error/(Hz s^{-1})	0.04
Satellite attitude stability/[$(^{\circ}) s^{-1}$]	1×10^{-3}

Table 7.6 Amplitude and phase error distribution in the range direction of SAR imaging

Error source	Error allocation value
Amplitude error/dB	First-order error 0.4, quadratic error 0.2, ripple 0.2, random error 0.2
Phase error/(°)	First-order error 25, quadratic error 20, triple error 10, quadric error 15, quintic error 20, random error 2
AD sampling jitter/ns	0.1

The amplitude and phase error in the range direction mainly refers to the amplitude and phase error without changing the characteristics of the system when the transmitting and receiving channels deviate from linearity, which will lead to the mismatch of range direction matched filtering, the widening of main lobe, the rise of sidelobe, and deteriorating the performance of range direction imaging. Table 7.6 gives the range direction of the amplitude and phase errors.

7.7.6.2 Ground Weighting Processing

In order to reduce the sidelobe level and increase the peak sidelobe ratio, a weighting function is usually added in the imaging process. The imaging processing weighting in the azimuth direction function (assuming Doppler center is 0) is as follows:

$$W_a(f) = \alpha + (1 - \alpha) \cos(2\pi f/B_d), \quad f \in [-B_d/2, +B_d/2]. \quad (7.20)$$

The formula of weighting function for imaging processing in the range direction is as follows:

$$W_r(f) = \alpha + (1 - \alpha) \cos(2\pi f/B_w), \quad f \in [-B_w/2, +B_w/2], \quad (7.21)$$

where $W_a(f)$ is the azimuth direction window function, $W_r(f)$ is the range direction window function, α is the shape factor of the weighted function, B_d is the Doppler processing bandwidth, B_w is the signal bandwidth, and f is the frequency.

7.7.6.3 Sidelobe Performance Analysis

Under the above conditions of amplitude and phase error distribution and weighting function of ground processing, Table 7.7 gives the prediction results of sidelobe performance of GF-3 satellite imaging mode. In all imaging modes, the design results of PSLR are lower than -20 dB, and the design results of ISLR are lower than -15 dB, which meet the design requirements.

Table 7.7 Design sidelobe performance for different imaging modes

Imaging mode	Specification/dB		Design sidelobe/dB	
	PSLR	ISLR	PSLR	ISLR
Spotlight mode	≤ -22	≤ -15	-23.7	-17.6
Hyperfine strip map mode			-23.2	-18.2
Fine strip map mode			-22.9	-17.1
Standard strip mode	≤ -20	≤ -13	-21.3	-15.3
Wide scan mode			-20.8	-17.7
Full polarization strip mode	≤ -22	≤ -15	-23.8	-16.7
Wave mode			-23.8	-16.7
Global observation mode	≤ -20	≤ -13	-20.5	-15.8
Extension of the incidence angle			-21.3	-15.3

7.7.7 Imaging Width

The imaging swath is defined as the effective imagery swath that can be obtained by processing all data in the range direction. The imaging swath mainly depends on the echo sampling points, beam pointing accuracy, initial echo sampling accuracy, and range migration. Table 7.8 gives the requirement on imaging swath, sampling point design, and swath design for each imaging mode. Through comparative analysis, the design of sampling points meets the requirements of imaging swath indicator. Generally, the larger the width, the higher the resolution, the more sampling points needed. The designed sampling points are the least in the global observation imaging mode and the most in the fine strip imaging mode.

Table 7.8 Design of amplitude width and sampling points for different imaging modes

Imaging mode		Swath requirement/km	Design of sampling points	Design swath/km
Spotlight mode		10 × 10	19,456–31,744	10 × 10
Hyperfine strip mode		30	17,408–29,696	30
Fine strip mode		50	15,360–29,696	50
Standard strip mode		130	18,432–41,984	95–150
Wide scan mode		500	14,336–21,504	500
Global observation mode		650	2048–3072	650
Full polarization strip mode		30	8192–10,240	20–35
Wave mode		5 × 5	8192–20,480	5 × 5
Extension	Low incidence angle	130	38,912–39,936	120–150
	High incidence angle	80	15,360–19,456	70–90

Table 7.9 Performance of noise equivalent sigma zero in different imaging modes

Imaging mode		Specification/dB	Noise Equivalent Sigma Zero (NESZ)/dB	
			Center	Edge
Spotlight mode		≤ -19	-28.15 to -19.7	-27.09 to -19.36
Hyperfine strip mode			-30.29 to -22.78	-24.64 to -21.1
Fine strip mode			-29.73 to -26.11	-23.81 to -19.66
Standard strip mode		Center ≤ -25 , Edge ≤ -21	-33.58 to -27.54	-26.91 to -21.48
Wide scan mode			-35.19 to -28.56	-28.52 to -22.57
Full polarization strip mode		≤ -19	-36.53 to -34	-33.06 to -28.43
Wave mode			-34.68 to -32.05	-31.44 to -26.74
Global observation mode	Extension	Center ≤ -25 , Edge ≤ -21	-40.32 to -34.43	-33.85 to -28.37
Low incidence angle			-27.74 to -27.27	-21.8 to -21.33
High incidence angle			-36.49 to -34.46	-32.25 to -27.95

7.7.8 Noise Equivalent Backscattering Coefficient $NE\sigma^0$

Noise equivalent backscattering coefficient refers to the target backscattering coefficient corresponding to the input signal with the same output power of the system noise, which reflects the SAR system's ability to detect weak scattering targets. For GF-3 satellite orbit and SAR payload parameters, the noise equivalent backscattering coefficient of each imaging mode system is shown in Table 7.9. In all imaging modes, the designed noise equivalent backscattering coefficients are lower than -19 dB, the scenario center is the lowest, and the edge is higher. This is mainly due to the antenna pattern.

7.7.9 Azimuth Ambiguity

Azimuth ambiguity refers to the ratio of signal intensity in azimuth ambiguity zone mixed in azimuth direction processing band to image intensity in the imaging area, which mainly depends on the characteristics of antenna pattern and the value of PRF. In addition, the estimation error of Doppler center and the width of Doppler processor will also affect the azimuth ambiguity.

When the radar works in squint mode, the yaw measurement error will cause the change of the radar squint angle and incidence angle, and the satellite platform yaw error will also cause estimation error of the Doppler frequency based on orbit. The yaw measurement error of satellite platform will affect the azimuth resolution, azimuth ambiguity, noise equivalent backscattering coefficient, phase error, peak sidelobe ratio of point target response, and integrated sidelobe ratio of SAR image.

Based on the antenna usage mode, PRF range, Doppler processor width, and error source values, the predicted azimuth ambiguity performance of satellites in various imaging modes is shown in Table 7.10. In all imaging modes, the design result of azimuth ambiguity is lower than -18 dB. In hyperfine strip map, full polarization strip map, and wave mode, the design result of azimuth ambiguity can reach -30 dB.

Table 7.10 Azimuth/range ambiguity performance of different imaging modes

Imaging mode		Resolution/m	Azimuth ambiguity/dB		Range ambiguity/dB	
			Indicator	Design result	Indicator	Design result
Spotlight mode		1	≤ -20	-26.89 to -20.08	≤ -20	-56.47 to -20.81
Hyperfine strip mode		3		-29.79 to -21.78		-43.64 to -22.04
Fine strip mode		5		-25.32 to -20.13		-36.69 to -20.01
Standard strip mode		25	≤ -18	-24.84 to -18.77		-31.64 to -20.31
Wide scan mode		100		-24.54 to -18.36		-31.64 to -20.31
Full polarization strip map mode		8	≤ -20	-32.06 to -20.07		-46.74 to -31.37 (co-polarization) -33.09 to -20.02 (cross polarization)
Wave mode		10		-32.06 to -20.07		-46.74 to -31.37 (co-polarization) -33.09 to -20.02 (cross polarization)
Global observation mode		500	≤ -18	-24.85 to -18.38		-31.64 to -20.4
Extension of the incidence angle	Low-end	25		≤ -20		-31.66 to -31.52
	High-end	25		≤ -20		-23.92 to -21.28

7.7.10 Range Ambiguity

The range ambiguity refers to the ratio of the signal intensity of the fuzzy region mixed into the mapping zone to the signal strength of the main observation zone, which mainly depends on antenna pattern characteristics and PRF values and is affected by beam width and beam pointing error. Based on PRF range, range beam width, and error source values, the range ambiguity performance prediction results of satellite imaging modes are shown in Table 7.10. In all imaging modes, the range ambiguity design results are lower than -20 dB, and can reach -56 dB in spotlight mode.

7.7.11 Radiation Error Source Analysis and Its Precision Control

Radiation accuracy reflects the capability of quantitative remote sensing of SAR system and is an important indicator of satellite-ground integration. Its influencing factors and error sources are listed in Table 7.11.

In the case of the above error sources, the radiation accuracy is predicted and the results are as follows:

- (1) Relative radiation accuracy is 0.9 dB (one scene), which meets the requirement that the relative radiation accuracy is better than 1.0 dB in one scene.
- (2) Relative radiation accuracy is 1.4 dB (one orbit), which meets the requirement that the relative radiation accuracy is better than 1.5 dB in one orbit.
- (3) Relative radiation accuracy is 1.7 dB (within three days), which meets the requirement that the relative radiation accuracy is better than 2.0 dB within three days.
- (4) The relative radiation accuracy is 2.4 dB (life cycle), which meets the requirement that the relative radiation accuracy of life cycle is better than 3.0 dB.
- (5) The absolute radiation accuracy is 1.69 dB, which meets the requirement that the absolute radiation accuracy is better than 2.0 dB.

7.7.12 Radiation Resolution

Radiation resolution is the ability to distinguish the backscattering coefficients of different targets in the SAR satellite imaging range, and it is a measure for the imaging quality level. The radiation resolution mainly depends on the equivalent view number and SNR of SAR images. The equivalent number of looks of various imaging modes and the theoretical radiation resolution performance are shown in Table 7.12.

Table 7.11 Error source value of SAR imaging influencing radiation accuracy

Error source		Value/dB
On-orbit error	Beam pointing error (bidirectional)	0.5
	Pattern measurement error	0.3
	Antenna gain instability	0.2
	Internal calibration	0.6
	A/D and BAQ error	0.2
Propagation error	Atmospheric attenuation	0.2
	Atmospheric scintillation	0.2
	Faraday effect	0.1
Noise interference	Integral sidelobe ratio	−13
	Azimuth ambiguity	−18
	Range ambiguity	−20
	$\Delta N(S/N = 6 \text{ dB})$	0.0542
Imaging processing		0.3
External calibration accuracy	Strip mode	0.5
	Scan mode	0.7

Note The satellite attitude pointing accuracy is 0.03°, and the antenna pointing accuracy in the range direction is 0.04°

In order to satisfy the resolution of 1–10 m, the radiation resolution is better than 3.5 dB, single-view processing can be achieved; the resolution of 25–500 m mode is better than 2.0 dB, and the equivalent multi-view requirement is between four and six views. At present, the working mode design with a resolution of 25–500 m is 6–8 views.

7.7.13 Verification of SAR Imaging Quality

In the concept phase, the concept and the realization of imaging quality are verified through the development, joint test, and test of the SAR subsystem engineering prototype. According to the experimental results, the performance satisfaction of SAR imaging obtained from the calculation and analysis is shown in Table 7.13.

Table 7.12 SAR imaging number of looks and radiation resolution

Imaging mode	Requirement/dB	Equivalent number of looks/views	Radiation resolution/dB		
			Designed(HH)	Designed(HV)	Designed(VV)
Spotlight mode	≤3.5	1 × 1	3.19 to 3.83	3.74 to 5.46	3.15 to 3.87
Hyperfine strip mode		1 × 1	3.11 to 3.48	3.43 to 4.53	3.08 to 3.50
Fine strip mode		1 × 2	3.17 to 3.43	3.64 to 4.51	3.12 to 3.46
Standard strip mode	≤2.0	3 × 2	1.54 to 1.76	1.73 to 2.41	1.53 to 1.77
Wide scan mode		2 × 4	1.35 to 1.46	1.44 to 1.83	1.34 to 1.47
Global observation mode		4 × 2	1.32 to 1.36	1.35 to 1.47	1.32 to 1.36
Full polarization mode	≤3.5	1 × 1	3.02 to 3.05	3.07 to 3.11	3.02 to 3.03
Wave mode		1 × 2	2.34 to 2.37	2.41 to 2.46	2.34 to 2.35
Extension of the incidence angle		3 × 2	1.53	1.68	1.52
	High-end	1.52 to 1.56	1.62 to 1.76	1.52 to 1.57	

Table 7.13 Analysis of SAR imaging performance

Image performance parameters		Requirement	Realization situation
Polarization isolation/dB		≥ 35	35.65
Polarization channel imbalance	Amplitude/dB	$\leq \pm 0.5$	$\leq \pm 0.39$
	Phase/(°)	$\leq \pm 10$	$\leq \pm 9.6()$ (roundtrip)
System sensitivity NEσ0/dB	Resolution 1–10 m	Edge is better than −19	≤ -19.07
	Resolution 25–500 m	Center is better than −25	≤ -26.78
		Edge is better than −21	The combination of transceiver links ensures that the equivalent Noise Equivalent Sigma Zero (NESZ) meets the design requirements
Azimuth ambiguity/dB	Resolution 1–10 m	< -20	Azimuth ambiguity ≤ -20.11
	Resolution 25–500 m	< -18	Azimuth ambiguity ≤ -18.34
Range ambiguity/dB		< -20	Range ambiguity ≤ -20.03
			Range ambiguity based on 11 wave position measured patterns is better than −20 dB
Sidelobe performance/dB	Resolution 1–10 m	PSLR < -22 ISLR < -15	PSLR ≤ -22.0 , ISLR ≤ -15.98
	Resolution 25–100 m	PSLR < -20 ISLR < -13	PSLR ≤ -20.26 , ISLR ≤ -16.70
Radiometric resolution/dB	Resolution 1–10 m	3.5	3.5 (Spotlight mode with 20°–40° incident angle)
	Resolution 25– 500 m	2.0	≤ 1.77
Absolute radiation accuracy/dB (3σ)		2.0 (long term)	1.79 (strip map); 1.99 (scan)
Relative radiation accuracy/dB (3σ)		1.0 (1 scene)	0.98
		1.5 (1 orbit)	1.29

7.8 Accuracy Analysis of Space-Borne SAR Imaging Positioning

Compared with optical images, SAR images have larger geometric distortion, which is not conducive to the interpretation of images by general users. The reason why SAR image is more geometrically distorted than optical image is the differences

in imaging mechanism and imaging geometry. The optical system is characterized by high angular resolution, which is the same as human visual system. There is no difficulty in viewing optical photographic images. SAR is a side-looking image with high range resolution. For example, the range of radar-facing slope is compressed on SAR image, and the range of radar-backing slope is lengthened on SAR image. Therefore, it is necessary to use range-Doppler localization method to perform SAR image localization interpretation based on SAR imaging mechanism.

7.8.1 Basic Principle of Space-Borne SAR Image Positioning

According to the geometric model of space-borne SAR system, the slant-range equation can be expressed as $\rho = |S - P|$, in which S represents the position vector of satellite (phase center of radar antenna) and P represents the position vector of ground target. The Doppler equation is

$$f_{dc} = -2 \frac{(V_S - V_T) \cdot (S - P)}{\lambda |S - P|}, \quad (7.22)$$

where f_{dc} is imaging Doppler center frequency, V_S , V_T represent the velocity vector of the satellite (radar antenna phase center) and the ground target, respectively, and λ represents the radar signal wavelength.

The equation of the Earth ellipsoid model is

$$\frac{x_T^2 + y_T^2}{(R_e + h)^2} + \frac{z_T^2}{R_p^2} = 1, \quad (7.23)$$

where R_e and R_p are the equatorial radius and polar radius of the Earth, respectively, and h is the height of the target relative to the hypothetical model. If the ground elevation information is unknown, the above equation will degenerate into the Earth ellipsoid equation. Based on this equation, space-borne SAR image localization can be realized, that is, system-level geometric correction processing.

7.8.2 Positioning Accuracy Error Source Analysis

Positioning accuracy is a constraint on the engineering system and belongs to the integration indicator of satellite and Earth, but mainly depends on the satellite system. There are many systematic error factors affecting the positioning accuracy of space-borne SAR images. The satellite system includes platform, payload, propagation, processing, and prior knowledge errors, as shown in Fig. 7.8.

After analysis, the positioning accuracy mainly depends on the measurement accuracy of satellite position and velocity, time accuracy, Doppler center estimation

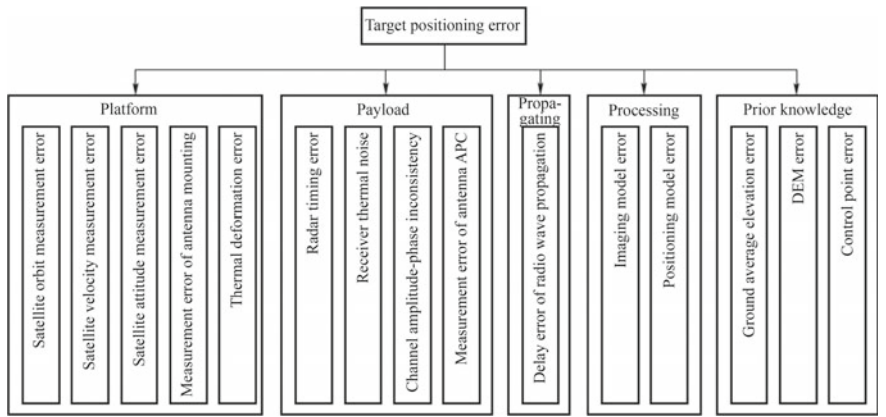


Fig. 7.8 Original error source affecting SAR image positioning accuracy

accuracy, and surface elevation accuracy, and the satellite attitude has little influence on the positioning accuracy of microwave image. Under the constraints of satellite system scheme and parameters such as orbit and angle of view, the main errors affecting image positioning accuracy are allocated and analyzed according to user’s requirements. Among them, the time delay measurement accuracy of SAR system, the initial accuracy of echo sampling, and the time accuracy of auxiliary data are the error sources related to SAR payload. See Table 7.14 for more details.

In terms of orbit measurement, by configuring dual-frequency GPS, the accuracy of its orbital position measurement can reach 30 m (3σ) under the real-time condition, and realize the satellite measurement error (along-track) of 0.6 m/s.

In terms of time synchronization system, in order to ensure the above requirements, the payload subsystem and the control subsystem are required to work under a precise and uniform time base, so that the satellite imaging data and the control measurement data have the same time base, and the accuracy of the satellite load data is improved. Considering the implementation of hardware time service, GPS receivers send full-second pulse signals to provide high-precision time services for related equipment, and its accuracy is better than 1 μ s. In terms of DEM, the current widely used elevation DEM data is the global elevation information acquired by the Shuttle Radar Topography Mission (SRTM) with an elevation accuracy of 16 m.

Table 7.14 Positioning accuracy error source parameter setting and influence on positioning accuracy

Systematic error source		Input error value	Positioning error/m
Along-track location error/m		30	26.65
Cross-track location error/m			26.65
Radial-track location error/m			170.57– 22.12
Velocity error	Along-track velocity error/(m s ⁻¹)	0.6	0.0–0.0
	Cross-track velocity error/(m s ⁻¹)		8.89 –76.27
	Radial-track velocity error/(m s ⁻¹)		56.94– 63.33
	Comprehensive velocity error/(m s ⁻¹)		57.63–99.13
Auxiliary data astronomical time error/s		0.005	33.31
Time delay measurement error of SAR system/ns		30	25.91–5.19
Echo sampling initial time error/ns		6	5.18–1.04
Ionospheric propagation delay error/ns		40	34.55–6.93
Surface elevation error/m	Elevation error	30	170.13–17.32
		48	272.22– 27.71
Synthetic error/m	Elevation error	30	256.49–115.00
		48	333.08–117.02

7.9 Space-Borne SAR Data Processing and Inversion Technology

7.9.1 Echo Signal Modeling Technology

The most important parameter in data processing of space-borne SAR is the slant distance from radar to target, which varies with azimuth time and can be defined by range model (signal model) equation. The equation of range model is used to simulate the slant distance curve in synthetic aperture time in the form of analytical expression. At present, the echo signal model for LEO SAR satellites is hyperbolic range model (equivalent squint model) plus “stop-and-go” model, and the echo signal model for medium and HEO SAR is fourth-order range model plus “non-stop-and-go” model.

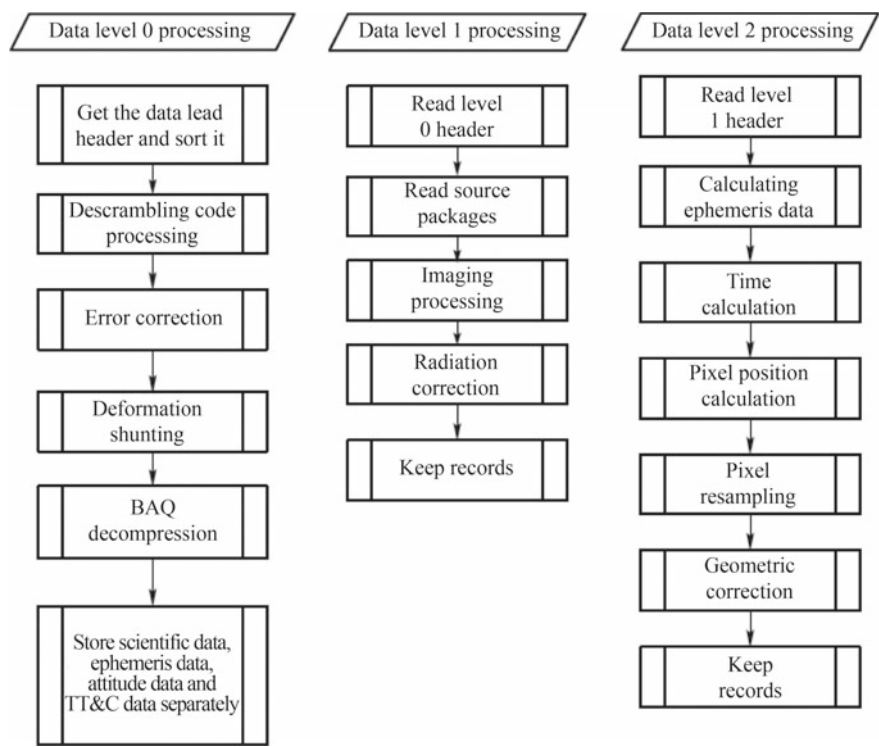


Fig. 7.9 SAR data processing flow

7.9.2 Data Processing Method

The raw data of the SAR satellite is received by the satellite ground station, and after pre-processing such as unpacking, the data processing center is provided with level 0 data products and other auxiliary products (track and attitude files, etc.). After receiving the 0-level data product, the data processing center will make it into a level 1 data product, and carry out product archiving and distribution services. At the same time, it is responsible for making a level 2 data product based on the level 1 product, and performing product archiving and distribution service. The general imaging data processing process is shown in Fig. 7.9.

7.9.3 Speckle Noise Suppression Technology

Due to the special coherence imaging mechanism of SAP, the target image with uniform scattering coefficient contains speckle noise, which makes its gray level uneven. Coherent speckle is an inherent deterministic interference phenomenon of

SAR images, which is caused by the coherence between scattered echoes of imaging targets. It contains part of the observed information. However, due to different polarization mode, complex background environment, imaging process, and resolution, the speckles in SAR images show great differences. It is difficult to analyze and utilize some of the information contained in SAR image with the current technology, which reduces the effective use of useful information in SAR image. Coherent speckle noise reduces the SNR of target image, which brings difficulties to target detection and recognition based on SAR image. The suppression of speckle noise in SAR image is an indispensable pre-processing step before processing SAR image. In the speckle suppression technology, it is necessary to consider how to better save the details of the image, such as texture information and edge information, while removing the speckle noise in the image.

At present, the research on the speckle reduction technology can be divided into two major categories, namely the multi-view smoothing technology used before imaging and the filtering technology used after imaging. The filtering technology after imaging can fall into two categories: spatial domain filtering technology and frequency domain filtering technology.

7.10 Application of SAR Remote Sensing Satellite

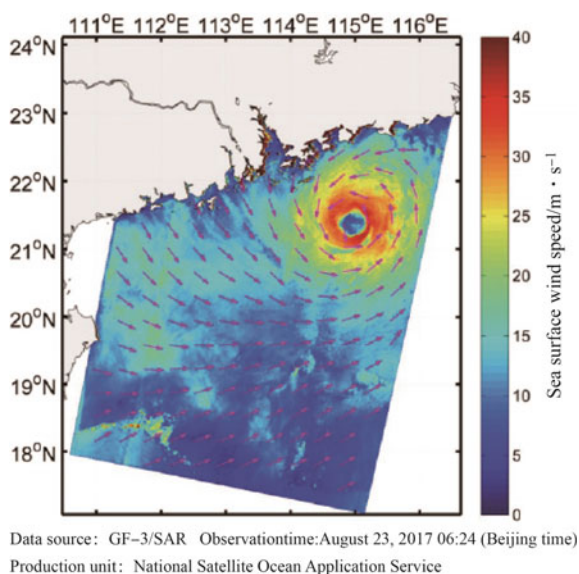
7.10.1 Application of Space-Borne SAR in Disaster Reduction

When natural disasters such as floods, landslides, and debris flows occur, it is necessary to understand the scope of the disaster in the first time, so as to effectively evaluate the disaster. Therefore, it is required that the repeated observation period can be set from several hours to several days as needed. For medium-scale natural disasters, such as floods in rivers and lakes, images with medium resolution and certain imaging coverage are required for monitoring. For the monitoring of the flood in urban areas or the damage about dykes and dams, high-resolution images are required for monitoring. Figure 7.10 shows the results of regional polarization decomposition on the Jiuzhaigou earthquake of the GF-3 satellite in August 2017 (red for buildings with three-dimensional spatial structure), which provides a strong support for disaster assessment.

7.10.2 Application of Space-Borne SAR in Marine

SAR data contains abundant ocean information and plays an increasingly important role in the field of ocean observation and application research. Firstly, SAR can acquire continuous ocean environment data by high-resolution imaging observation

Fig. 7.11 GF-3 satellite fully polarized strip map mode sea surface wind field inversion results, reprinted from Ref. [2], copyright 2018, with permission from Satellite Applications



possible. Ship target detection based on space-borne SAR has important theoretical significance and application value in marine transportation, fishery monitoring, and oil spill detection. Figure 7.12 illustrates the ship detection results using a GF-3 SAR image.

7.10.4 Detection on Ground Moving Target by Space-Borne SAR

The ground moving target detection system based on space-borne SAR platform provides the possibility for wide-area topographic mapping, surveillance, reconnaissance, ground target detection, positioning and tracking, and has essential application value. Because the high-speed motion of space-borne SAR platform results in clutter Doppler broadening, which will submerge slow targets, clutter suppression is required. The GMTI mode of space-borne SAR can realize high-resolution moving target detection. See Fig. 7.13.

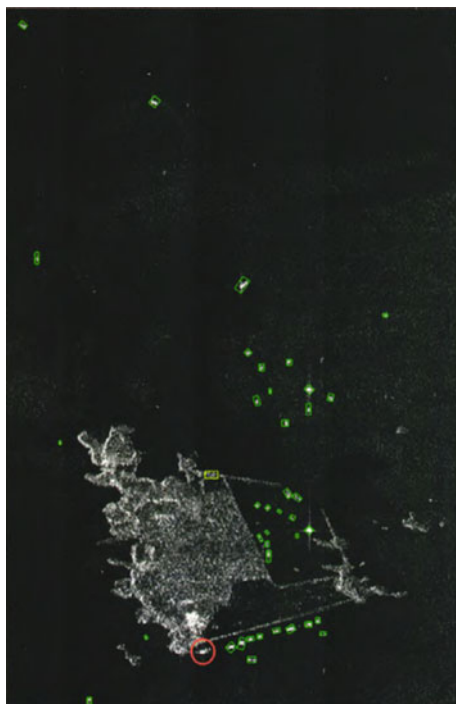


Fig. 7.12 Ship detection results of GF-3 SAR image, reprinted from Ref. [3], copyright 2017, with permission from Journal of Radars

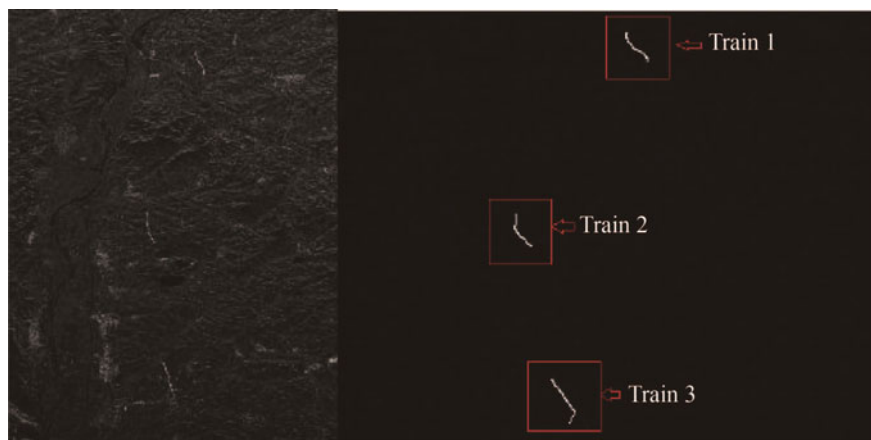
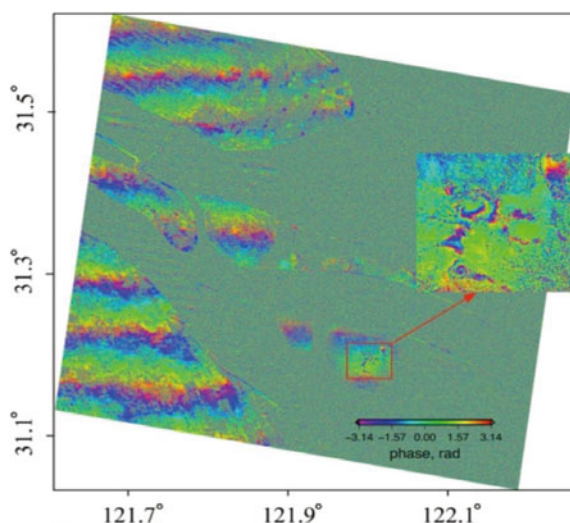


Fig. 7.13 Detection results of moving targets along Datong–Qinhuangdao Railway by GF-3 Satellite, reprinted from Ref. [4], copyright 2018, with permission from Satellite Applications

Fig. 7.14 Interferogram of GF-3 Satellite in Shanghai City, reprinted from Ref. [4], copyright 2018, with permission from Satellite Applications



7.10.5 Application of Space-Borne SAR Interferometric Mapping

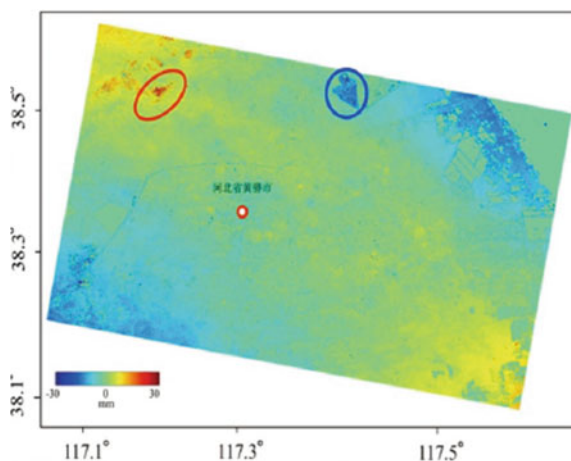
SAR interferometry is an advanced remote sensing information acquisition technology based on traditional SAR, by which two pairs of antennas or repetitive orbits are used to image the same ground target twice from different angles, forming a complex image pair. The three-dimensional information of the Earth's surface or the information of ground objects changes is extracted through the phase difference of two complex images obtained by interferometric processing. Compared with optical remote sensing satellite, interferometric SAR satellite system is not affected by illumination and clouds, and its data processing speed is faster, and can cover the vast area of the Earth quickly.

After a series of interference processing of GF-3 raw data, such as accurate image registration, flat ground removal effect, noise reduction filtering, and phase unwrapping, the three-dimensional topographic inversion results can be successfully obtained. See Fig. 7.14.

7.10.6 Differential Interference Application of Space-Borne SAR

Through processing radar interferometric images acquired from GF-3 satellite repetitive orbit in area Huanghua, the Province Hebei, the surface deformation in this area is obtained. The time baseline is 29 days, and the space vertical baseline is 250 m. The phase has been unwrapped and transformed into the deformation. The red color

Fig. 7.15 Deformation measurement results of GF-3 Satellite in Area Huanghua, Province Hebei, reprinted from Ref. [4], copyright 2018, with permission from Satellite Applications



indicates that the surface is far from the satellite (i.e., ground subsidence), the blue indicates that the surface moves toward satellite (i.e., ground elevation), and the red elliptical region is located in Wetland Nature Reserve Nandagang with obvious ground elevation signals (Fig. 7.15). The advanced design of the satellite GF-3 is fully verified.

7.11 Conclusion

The system design of high-resolution SAR satellite is based on the application requirement; according to the scattering characteristics of the interested target, the working frequency and polarization form are determined; satellite orbit parameters are determined according to the revisit period and coverage range; SAR payload parameters, satellite configuration, energy, data transmission and attitude control, thermal control, and TT&C system are completed according to the mission requirements. During the system design, the influence of various factors on the final imaging quality should be fully considered in the system design process, and quantitative analysis should be carried out during the analysis process. The final results are the basic constraints for SAR satellite development.

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Chapter 8

Design and Analysis of High-Precision Microwave Remote Sensing Satellite System



8.1 Overview

Over 70% of the Earth's surface is covered with oceans rich in renewable and nonrenewable energy, which plays an important role in regulating the global climate. The ocean microwave remote sensing satellite system has become an irreplaceable high-tech means to understand, research, develop, utilize, and manage the ocean by its advantages of all-time, all-weather, large area, multiscale, synchronization, fast, high frequency, short-cycle, long-term continuous observation, etc., that is not limited by geographical location and human conditions, as well as the coverage ability of critical environmental and politically sensitive sea areas. Therefore, ocean environment detection by means of ocean microwave remote sensing satellite system has been highly valued. The military struggle around ocean resources and ocean territory is becoming increasingly fierce. The superpowers, traditional maritime powers, and coastal developing countries all attach great importance to the development of ocean microwave remote sensing satellite technology.

After years of development, the global ocean microwave remote sensing satellite system has been developed from a single detection method to a fusion of multiple means of detection, so that application range and depth of microwave remote sensing data are improved, and the ability of early warning and prediction of ocean environmental disasters and the level of global climate change monitoring are effectively developed. Ocean monitoring plays an important role in safeguarding ocean rights and interests, military security, resource survey, environmental monitoring and disaster prediction. Table 8.1 shows the advanced ocean microwave remote sensing satellites in the world in recent years.

Based on the system design and application experience of China's ocean microwave remote sensing satellite, this chapter focuses on the system design method for high-precision microwave remote sensing applications, including the design elements of radar altimeter/microwave scatterometer/microwave radiometer, error source analysis and precision control, radiation calibration, data processing, etc.

Table 8.1 Global ocean microwave remote sensing satellites

Satellites	Country/region	Main payload	Working frequency band	Measuring accuracy	Principal uses
WindSat 2003	USA	Microwave radiometer	6.8/10.7/18.7/23.8/37 GHz five-channel, fully polarized	Swath 1450 km, resolution 25 km, temperature measurement accuracy better than 1 K	Sea surface wind direction measurement
Jason-2 2008	France/USA	Altimeter of sub-satellite point	13.58/5.3 GHz	Swath of 2.2 km and height measurement accuracy of 2.5-3.4 cm	Sea surface height measurement
Smos 2009	Europe	Synthesis aperture radiometer	1.4 GHz	Swath is 1000 km, the resolution is 50 km, and the accuracy of salinity measurement is 0.1 psu.	Soil Moisture and Seawater Salinity Detection
CryoSat 2009	Europe	Interferometric radar altimeter	Ku band	Height measurement accuracy 0.17-3.3 cm	Measurement of thickness variation of ocean ice sheets, accurate monitoring of polar ice and ocean ice floes
Aquarius 2011	USA	Push-broom polarized microwave radiometer and scatterometer	1.413/1.26 GHz		Sea surface salinity detection
Sentinel-3 2013	Europe	Land-sea imager, radiometer, radar altimeter	Ku/C band	Height measurement accuracy 3 cm	Ocean color, sea and land surface temperature, sea surface and ice topography

(continued)

Table 8.1 (continued)

Satellites	Country/region	Main payload	Working frequency band	Measuring accuracy	Principal uses
Saral2013	India/Europe	Synthesis aperture altimeter	35.75 GHz	Swath 10 km	Ocean monitoring
Jason-32016	France/USA	AMR Altimeter of sub-satellite point AMR	13.58/ 5.3 GHz	Swath 2.2 km, height measurement accuracy 2.5-3.4 cm	Sea surface height measurement

8.2 Task Requirements and Payload Configuration Analysis

The core payloads of microwave remote sensing satellite include radar altimeter, microwave scatterometer, microwave radiometer, calibration radiometer, and synthetic aperture radar, in which Synthetic Aperture Radar (SAR) has been discussed in detail in Chap. 7.

8.2.1 Ocean Dynamic Environment Observation Requirements

In order to improve the accuracy and timeliness of ocean disaster prediction, the real-time and quantitative monitoring data of wind field, wave field, current field, and storm surge at sea should be obtained using all-time, all-weather, short-period, and high-precision remote sensing technology, so as to realize the systematical multi-scale, multifactor, large area, real-time, and dynamic monitoring of ocean dynamic environmental parameters according to the requirements on operational real-time monitoring of ocean environmental parameters such as sea ice, storm surges, sea surface winds, and ocean waves within the jurisdictional waters.

8.2.1.1 Observing Factors

In order to obtain the monitoring information of ocean dynamic environment, such as sea surface wind field, sea state prediction, storm warning, local ocean gravity field, local geoid, ocean circulation, it is necessary to detect important sea state parameters such as sea surface wind field, sea surface height field, effective wave height, ocean gravity field, ocean circulation, and sea surface temperature field, so as to improve

Table 8.2 Observing factors of ocean microwave remote sensing satellite

Detecting factors	Uses
<i>Main factors</i> Sea surface wind field, sea surface height, effective wave height, gravity field, ocean circulation, sea surface temperature	<i>Main uses</i> Sea surface wind field, sea state prediction, storm warning, local sea surface/bottom topology, local ocean gravity field, local geoid, ocean circulation
<i>Other factors</i> Geoid, ice height, water vapor content	<i>Other uses</i> Ocean dynamic process research, large and mesoscale weather processes, precipitation forecast, surface classification, and global change

the accuracy of ocean disaster prediction and better serve the national economy. Tables 8.2 show the corresponding relationship between detection elements and their uses.

8.2.1.2 Accuracy of Observing Factors

Ocean dynamic environmental parameters such as sea surface wind field, sea surface height field, wave field, ocean gravity field, ocean circulation, and sea surface temperature field can be detected by ocean microwave remote sensing satellite. These parameters are complex and variable, and shall be observed jointly by various detection means to improve the measurement accuracy of observed factors. At present, the typical detection accuracy requirements on observed factors are as follows:

1. Vector wind speed range: 2-24 m/s;
2. Vector wind direction accuracy: 20°;
3. Vector wind speed accuracy: 2 m/s or 10%;
4. Comprehensive height measurement accuracy of post-event survey: less than 10 cm;
5. Measuring range of effective wave height: 0.5–20 m;
6. Measuring accuracy of effective wave height: 0.5 m or 10%;
7. Sea surface wind speed: measuring range 7–50 m/s; measuring accuracy 2 m/s or 10%;
8. Sea surface temperature: measuring range 100–300 K, measuring accuracy 1.0 K.
9. Sea ice observation: ice cover 15%, thickness 2 m;
10. Precision of atmospheric water vapor content: 10%.

8.2.2 Analysis of Remote Sensor Configuration Scheme

In order to accomplish the mission of observing the ocean dynamic environment, satellite shall be equipped with radar altimeter, microwave scatterometer, microwave radiometer, calibration radiometer, and other microwave remote sensors. Considering

Table 8.3 Main detection factors and uses of satellite payload

Payload	Detection factors	Uses
Radar altimeter	Sea surface height, effective wave height, gravity field, oceanic circulation, geoid	Sea surface wind field, sea state forecast, storm warning; Researches on local sea/bottom topography, local ocean gravity field, local geoid, ocean circulation, El Niño, sea-air exchange; ocean dynamic process research, large and mesoscale weather process, precipitation forecast, surface classification, global change
Microwave scatterometer	Sea surface wind field	
Microwave radiometer	Sea surface temperature, sea surface wind speed, and water vapor content	
Calibration radiometer	Atmospheric and water vapor content	Altimeter calibration

the complexity and interaction of ocean phenomena, the synchronous observations of various instruments shall be compensated and calibrated to achieve the following objectives:

- (1) The global high-resolution ocean geoid and gravity field are obtained by using the sea surface echo information measured by radar altimeter.
- (2) Using the sea surface echo information measured by radar altimeter, the global wave data is obtained to improve the ability of early warning and prediction of ocean environmental disasters.
- (3) The global sea surface wind field is obtained using the backscatter coefficient information measured by microwave scatterometer, thus providing services on ocean environment prediction and storm disaster warning.
- (4) The sea surface brightness temperature measured by microwave radiometer is used to obtain all-time, all-weather, and wide-range sea surface temperature information, serving for fishery prediction, medium and long-term climate prediction, and global climate change.
- (5) The atmospheric and water vapor parameters are measured using calibrated radiometer for the error correction of radar altimeter.
- (6) The complete information of sea surface wind field is obtained through the synchronous observation of low wind speed and high wind speed by microwave scatterometer.

The main detection factors and applications of satellite payloads are shown in Table 8.3.

8.2.3 Constraints on Orbit Design

The following factors are to be considered to determine the orbit altitude:

1. Atmospheric drag can gradually decrease half-long axis of orbit and the orbit altitude, so the satellite operation period is shortened, that is, the average angular velocity of satellite operation increases. Eventually, the satellite ground trajectory deviates from its nominal position and drifts eastward. The lower the orbital altitude, the greater the impact of atmospheric drag on the satellite orbit is.
2. The higher the orbit, the longer the arc that can be observed from the ground TT&C station. The increase of orbital observation arc is beneficial to the accuracy of orbital measurement. More importantly, the higher the orbit, the less the influence of atmospheric drag on the accuracy of orbit measurement will be. In addition, the higher the orbit is, the less the influence of the high-order term of the gravitational field (shortwave variation part) on the orbit is, which contributes to reducing the error of the dynamic model and improving the accuracy of orbit measurement.
3. The higher the orbit, the higher the requirement for the launch vehicle of the satellite. Therefore, the carrying capacity of the launch vehicle should be considered when determining the orbit altitude.
4. The higher the orbit, the higher the requirement of satellite launch power is.

Based on the above factors and the fact that microwave remote sensing has no strict requirements for solar illumination conditions, the satellite adopts a dawn–dusk orbit at an altitude of about 1000 km, which means the orbit in full sunshine for most of the time and favorable conditions for the power supply system. Finally, the local time of descending node is determined at 6:00 am.

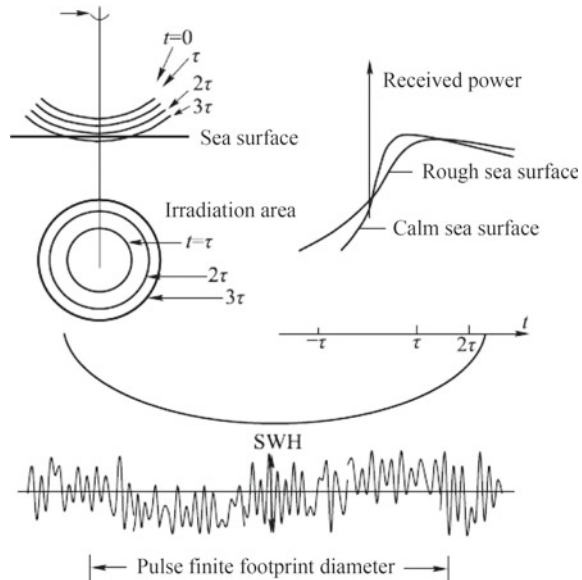
8.3 Design and Analysis of Radar Altimeter

Radar altimeter is used to measure sea surface height, effective wave height, and wind speed. Further inversion results of radar altimeter data can be applied to ocean geophysics, ocean dynamics, ocean climate and environment monitoring, sea ice monitoring, etc. Radar altimeter plays an important role in many fields, such as ocean disaster prevention and mitigation, ocean resources development, and global change research.

8.3.1 Principle of Radar Altimeter

The radar altimeter operates in a pulse limited footprint mode, that is, the pulse width footprint is smaller than the antenna beamwidth footprint, as shown in Fig. 8.1. The radar altimeter emits pulses with a pulse width of τ perpendicular to the sea surface. Its footprint gradually expands from point to circle. When $t = 2h/c + \tau$, the footprint in the circle area reaches its maximum, thereafter its form is expanded into a ring, however, their area remains unchanged in this process. Therefore, the echo power

Fig. 8.1 Echo of radar altimeter limited footprint



gradually increases from 0 to the maximum, forming the slope guide edge of the receiving power curve; after that, the echo power keeps the maximum, forming the flat top area of the curve. The receiving power of the altimeter can be expressed as

$$P_r(t) = P F_s(t) \times q(t) \times S_r(t), \quad (8.1)$$

where $P_r(t)$ represents the average receiving power (W); $P F_s(t)$ is the impulse response of the flat sea surface; $q(t)$ is the height probability density function of the scattering elements on the ocean surface; and $S_r(t)$ is the point target response of the radar system.

The half-power point of radar altimeter receiving power slope guiding edge corresponds to the mean sea level, and the height of radar altimeter relative to sea level can be obtained by measuring it and the propagation time between radar altimeter and transmitting pulse; the slope of guiding edge is inversely proportional to the effective wave height of sea surface, and the effective wave height of sea surface can be directly inverted by slope measurement. The backscattering coefficient is estimated by the echo power, and the satellite pointing error is estimated by the slope of the echo descent edge and the trailing time.

8.3.2 Design and Analysis of Radar Altimeter

Radar altimeter has the following functions: measuring sea surface height, effective wave height, and wind speed of sea surface at sub-satellite point; using dual-frequency system to calibrate ionospheric delay; correcting the drift of the instrument using internal calibration mode.

8.3.2.1 Measurement of Ocean Dynamic Topography

The altimeter measures the distance R between the satellite and the sea surface by transmitting and receiving pulses to and from the surface of the sea. The orbital altitude of the satellite can be obtained through Satellite Laser Ranging (SLR), Doppler Orbitography by Radio-positioning Integrated on Satellite (DORIS) as well as GPS orbit determination technology and orbital dynamics equation, that is, altitude S of the satellite itself relative to the Earth reference ellipsoid. As depicted in Fig. 8.2, Sea Surface Height (SSH) is the difference between the satellite altitude S and the altimeter ranging value R , which can be expressed as

$$\text{SSH} = S - R. \quad (8.2)$$

In case of no perturbation (wind, turbulence, tide, etc.), sea-level altitude is called geoid, which is mainly affected by changes in the gravitational field of the Earth;

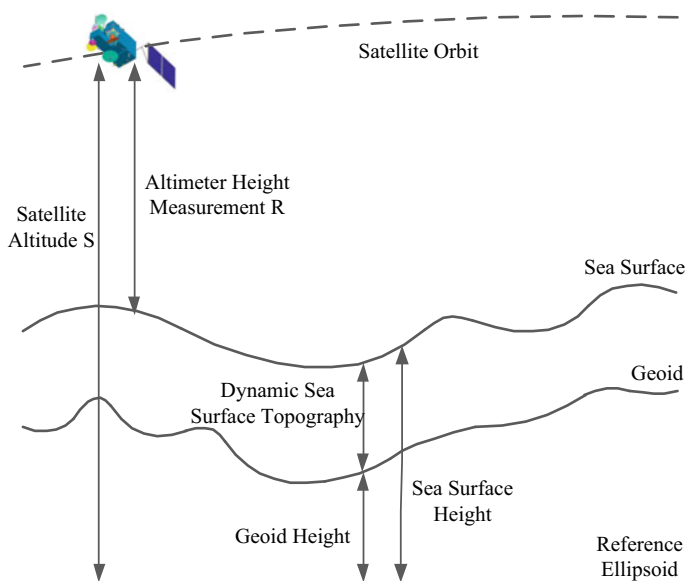


Fig. 8.2 Altimetry principle of radar altimeter

ocean circulation or dynamic topography consists of permanent static components (circulation caused by rotation, etc.) and highly variable components (wind, tide, seasonal variation, etc.) with an average change of magnitude of 1 m. Therefore, dynamic terrain can be obtained by subtracting the geoid height from SSH.

8.3.2.2 Effective Wave Height Measurement

The effective wave height can be determined by the shape of radar echoes. For example, the calm sea surface echoes the pulse intensively, while the rough sea surface broadens the pulse.

Because of the sea surface undulation caused by waves, the pulses emitted by radar altimeter on the wavefront of its spherical wave are first reflected by the crest of the sea surface and later by the trough, which broadens the rise of the echo signal. According to the relevant physics principles, the average intensity of the reflected signal varies with time as follows:

$$P(t) = K \frac{\chi_w}{s^2 H^3} \left[1 + \operatorname{erf} \left(\frac{t}{t_p} \right) \right] \exp \left(-\frac{2t}{t_s} \right) \text{SSH} = S - R, \quad (8.3)$$

where $\chi_w = c\tau/[4(\ln 2)^{1/2}]$; $c = 30$ cm/ns; H is satellite altitude (m); τ is the half-power width of the transmitting pulse; $t_p = (2/c)(\chi_w^2 + 2\sigma_h^2)^{1/2}$, σ_h is RMS wave height at sea level (the relation with effective wave height: $\text{SWH} = 4\sigma_h$); $t_s = 2H\Psi_e^2/c$, $1/\Psi_e^2 = (8\ln 2)/\Psi_e^2 + [(1 + H/a_e)/s]^2$, a_e is Earth radius, Ψ_e is half-power width of the antenna; $\operatorname{erf}(X)$ is the error function of X ; K is a constant related to antenna, transmission path, and reflection interface.

The larger the wave height, the larger the broadening of the echo signal and the smaller the slope. Therefore, the rising edge slope of the echo signal is inversely proportional to the sea surface effective wave height, approximately. Through the processing and analysis of radar altimeter data, a variety of physical parameters related to ocean phenomena can be obtained, as shown in Table 8.4.

Table 8.4 Relationship between radar altimeter measurement and ocean physical parameters

Parameters to be measured	Geophysical parameters	Ocean surveying and mapping products
Echo delay time	Satellite altitude	Ocean geoid, turbulence position and velocity, and ice topography
Waveform rising edge	Sea surface height, distribution, and standard deviation	Effective wave height
Amplitude	Backscattering coefficient	Sea/ice boundary and sea surface wind velocity
Trailing time	Satellite pointing and sea/ice tilt	Ice slope

8.3.2.3 Wind Velocity Measurement

The wind speed can be determined according to the echo pulse intensity of radar altimeter. The calm sea surface is a strong mirror, while the rough sea surface with a weak scattering reduces the echo amplitude. There is usually a strong correlation between wind speed and wave height. The total scattering power can be used to observe sea ice content, turbulent boundary, and ocean wind speed.

The sea surface can generate centimeter-scale waves under the action of wind, which will cause the change of sea surface roughness (mean square slope of sea surface). According to scattering theory, the relation between radar backscattering cross section σ_0 and mean square slope of sea surface $\bar{s}^2$ is as follows:

$$\sigma_0(\theta) \frac{|R(0)|^2}{\bar{s}^2} \sec^4 \theta \exp\left(\frac{\tan^2 \theta}{\bar{s}^2}\right), \quad (8.4)$$

where $|R(0)|^2$ is the Fresnel reflection coefficient and θ is incident angle of radar beam. The mean square slope $\bar{s}^2$ of the sea surface and the wind speed U of the sea surface approximately satisfy the following linear relationship:

$$\bar{s}^2 \propto U \quad (8.5)$$

In other words, when the incident angle of radar altimeter $\theta = 0$, there is an inverse relationship between the backscatter cross section and the surface wind speed, from which the wind speed can be calculated.

8.3.2.4 Analysis and Determination of Key Technical Specifications

By the radar altimeter of the satellite HY-2 with Ku and C dual-frequency pulse finite system, the distance between satellite and sea surface at sub-satellite point can be accurately measured with the ranging accuracy of better than 4 cm and the comprehensive height measurement accuracy of less than 10 cm. After the comprehensive processing of system data, the system can meet the requirements of effective wave height measurement range of 0.5–20 m and measurement accuracy of less than 0.5 m or 10%. Radar altimeter has an internal calibration mode to correct the drift of the instrument and can take into account both sea ice and land measurements. The main design and analysis factors of radar altimeter are listed below:

- (1) **Operating frequency**, by which ITU, ionospheric correction, user, engineering achievable, and EMC requirements on the whole satellite should be mainly considered.
- (2) **Signal bandwidth**, by which main factors to be considered are ranging resolution and accuracy.
- (3) **Transmitting power**, by which main factors to be considered are orbit height, distance measurement accuracy, and engineering feasibility.

- (4) **Pulse compression ratio** mainly depends on the required transmitting power, ranging accuracy, and engineering feasibility.
- (5) **Antenna gain**, by which main factors to be considered are the footprint size and measurement accuracy of the sub-satellite point.
- (6) **Measuring accuracy** mainly depends on the allocation of radar altimeter index, signal bandwidth, SNR, etc.
- (7) **Measurement range of backscattering coefficient** mainly depends on the dynamic range and SNR of the system.
- (8) **The measurement accuracy of backscattering coefficient** mainly depends on the system correction accuracy, etc.
- (9) **High accuracy of integrated measurement.** The final result of data processing of application system related to orbit determination accuracy, etc.
- (10) **Measuring range of effective wave height.** The final processing result of application system data.
- (11) **Measuring accuracy of effective wave height** mainly depends on system correction accuracy and SNR.

8.3.3 Configuration of Radar Altimeter and Topology

Radar altimeter is mainly composed of the following equipment and high-frequency cables of waveguide components (the block diagram is shown in Fig. 8.3).

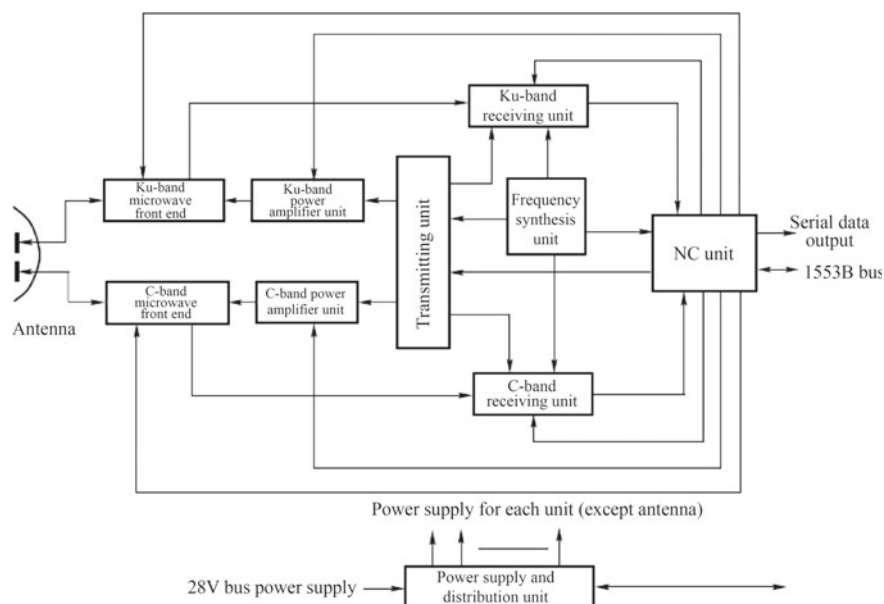


Fig. 8.3 Configuration and topological structure of radar altimeter

An antenna unit completes the transmitting and receiving tasks of Ku band and C band signals with the pulse limited working mode.

A microwave front end includes Ku band and C band front end, which, respectively, include a circulator, a microwave switch, a fixed attenuator, a directional coupler, etc., and the whole front-end network is controlled by instructions to implement transmission, reception and internal calibration switch control.

A power amplifier unit consists of two pulse solid-state power amplifier respective in Ku band and C band power amplifier.

A frequency synthesizer unit provides the frequency for each part of the instrument.

A transmitting unit includes Direct Digital Synthesizer (DDS) module, frequency doubling up-conversion module, and transmitting module. Under the trigger of the control signal, the Chirp signal generated by DDS is processed by frequency conversion, and two sets of transmitting signals in Ku band and C band are generated as input of the power amplifier. The unit generates two sets of de-chirp local oscillator signals in Ku band and C band simultaneously.

A receiving unit includes low noise amplifier, de-chirp mixer, IF receiver and phase detector, and finally generates orthogonal I/Q signal.

A NC unit includes altimeter tracker and bus communication, in which the altimeter tracker completes the acquisition functions of orthogonal I/Q channels, Fast Fourier Transform (FFT), tracking processing, and timing control; the bus communication part completes the communication with satellite OBDH, i.e., acquire satellite auxiliary data (including time code, attitude code, injection data, engineering parameters and some remote sensing data, etc.) through 1553B bus and sends the scientific data generated by the altimeter to the data transmission subsystem through the high-speed serial channel.

A power supply and distribution unit converts the bus power supply voltage into various voltages required by the equipment.

8.3.4 Design of Working Mode

Normal working mode

Altimeter is always in working state during the satellite is on-orbit, and remote sensing data acquired is transmitted to ground station through data transmission subsystem. The altimeter has the function of calibrating in a certain period, correcting the drift of the instrument, and sending the calibration data to the ground station through the data transmission subsystem.

Emergency working mode

When the subsystem fails, self-protection function should be available. At the same time, interference with other subsystems should be avoided.

8.3.5 *Height Measurement Precision Analysis and Control of Radar Altimeter*

For ocean microwave remote sensing satellites, the critical problem is the analysis of the influence of various aspects involved in sea surface height measurement on the final measurement accuracy. Therefore, the key to the system design of the satellite is the analysis and allocation of the measurement error index of the altimeter.

8.3.5.1 Analysis of Major Error Sources

There are many error sources in sea surface altitude measurement and dynamic topographic survey, which are complex functions of position and scale.

1. The altitude of the satellite from the center of the Earth itself must be known, which can be obtained by the accurate mathematical model of the tracking system or the dynamics system of the aircraft. The latter requires a model of gravitational field of the Earth, which cannot be very accurate, but it is a constant function of time. In addition, appropriate mechanical models of atmospheric drag and radiation pressure from the sun and the Earth required vary in time and space and depend on some variables, such as atmospheric temperature, satellite orientation.
2. The altimeter itself has multiple sources of error: The altimeter TOPEX has an accuracy of about 2.0 cm, but a series of calibrations must be carried out on the altimeter to get the true value of altitude matched with the accuracy. Since both atmospheric water vapor and ionosphere have effects on the propagation velocity of electromagnetic waves, they should also be corrected. In addition, the ocean surface is complex, rough, and dynamic, which also affects altimetry.
3. Altimeter measurement is to obtain not only the altitude of the ocean surface, but also the topographic map G caused by the dynamic characteristics of the ocean, which is the difference between the altitude of the ocean surface SSH and the geoid height. Therefore, the information about the shape of the geoid should be gained for calculating the ocean topography through the sea surface altitude measured by satellite. The change of the geoid relative to the flat ellipsoid reference surface is about 100 m. In contrast, the change in ocean topography relative to the geoid caused by ocean dynamic characteristics is only about 1 m. If the constant rotation speed of the Earth is to be calculated, the geoid must be accurately determined. Conversely, if only the variation of the rotation speed of the Earth over time is to be obtained, a rough calculation of the geoid value is enough.
4. The correlation between the rotation speed of the Earth's surface and the velocity below a certain depth of the sea surface involves the density field below the sea surface. Although this cannot be obtained from space, it can be obtained by modeling using other oceanographic methods.

In order to make full use of the ocean surveying in the large scale, the accuracy of sea-level surveying must reach several centimeters on a spatial scale of hundreds to thousands kilometers. For this reason, various errors must be reduced, including errors affecting sea level surveying and errors affecting survey interpretation. The error sources are summarized as follows:

- **Orbital error** is the main error of satellite altimetry, which is caused by the radial error of orbit and the track error.
- **Coordinate transformation error** is caused by inconsistencies between different coordinate systems in altimetry;
- **Ionospheric error**, an altimetry error, is caused by ionospheric refraction.
- **Tropospheric error**, an altimetry error, is caused by atmospheric refraction.
- **Sea wave electromagnetic error** is caused by that the ability of valley reflecting pulse is better than that of the peak, the center of gravity of echo power distribution deviates from the mean sea level and tends to the valley.
- **Satellite platform error** is a measurement error, which mainly caused by antenna pointing deviation;
- **Calibration error** is an error when performing ranging calibration on the satellite.
- **Instrument error** is caused by the accuracy of the instrument itself.
- **Geoid model error**.

The error sources of the satellite altimeter are shown in Fig. 8.4.

8.3.5.2 Orbital Error Source Analysis and Precision Control

At present, various precise observation networks for satellite tracking have been established worldwide. The used high-precision observation technologies include Satellite Laser Ranging (SLR), Global Positioning System (GPS), Doppler Orbitography and Radio-positioning Integrated by Satellite (DORIS), Precise Range And Range-rate Equipment (PRARE), US Surveying and Mapping Agency Transport Network and Business Tracking Network (TRANET/OPNET) and Tracking and Data Relay Satellite System (TDRSS). A brief introduction to these observation techniques and corresponding observation networks is shown in Table 8.5.

Relevant research indicates that under normal observing conditions, for LEO satellites, if the dual-frequency satellite-borne GPS receiver is used to determine the orbit independently, the orbit accuracy can be basically guaranteed within 15 cm. Due to the low cost and lightweight characteristics of onboard GPS equipment, and the advantages of all-weather, high-precision, and continuous observation, this technique is increasingly used as POD devices in low-orbit satellites for remote sensing, meteorology, or ocean altimetry. From T/P satellite launched in 1992 to GRACE satellite launched in 2002, more than 40 satellites have been equipped with onboard GPS receivers.

Due to the poor tracking coverage of the SLR tracking system, the high-precision orbit determination in full-segmental arc is difficultly implemented only by it.

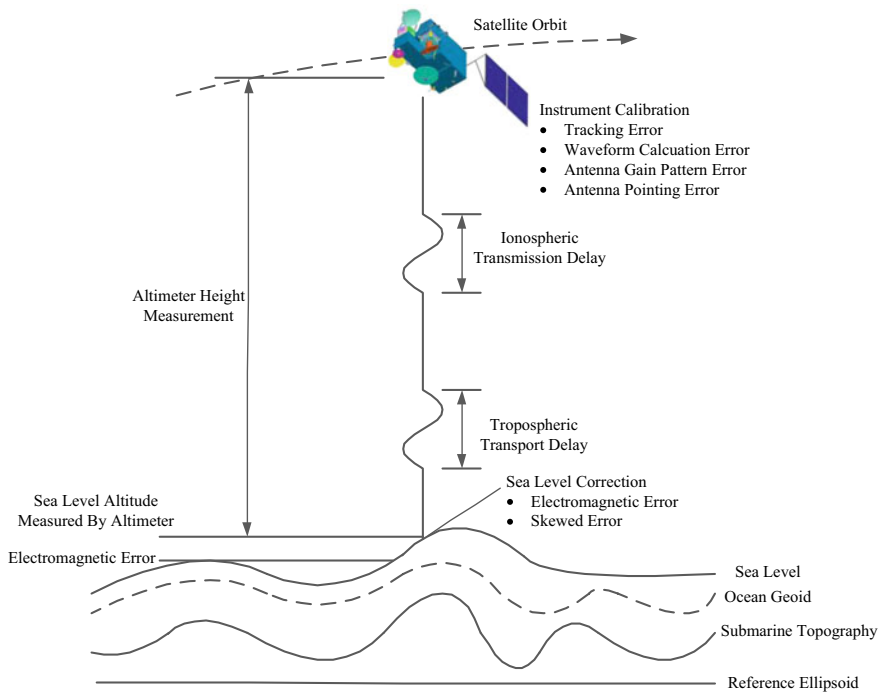


Fig. 8.4 Schematic diagram of the error sources of satellite altimetry, reprinted from Ref. [1], copyright 2015, with permission from Beijing: China Aerospace Publishing House

Table 8.5 Current altimeter satellite tracking system and approximate tracking accuracy

Tracking technology	Observation	Measurement accuracy	Launch satellite
SLR	Slant distance/cm	0.5–5	All satellites except Geosat
DORIS	Change rate of slant distance/(mm s ⁻¹)	0.5	T/P, Jason1, Envisat
PRARE	Slant distance/cm	2.5	ERS2
	Change rate of slant distance/(mm s ⁻¹)	0.25	
GPS	Phase/cm	0.2–0.5	T/P, Jason1, Envisat
TRANET/OPNET	Change rate of slant distance/(mm s ⁻¹)	2–10	Seasat, Geosat
TDRSS	Change rate of slant distance/(mm s ⁻¹)	0.3	T/P

However, the certain multi-segmental arc SLR observations can be a useful supplement to continuous GPS observations, which will effectively improve the reliability and stability of GPS observations, because SLR has a high tracking accuracy and is an independent system that does not depend on other POD systems. Moreover, SLR observations are regarded as the objective standard of GPS orbit determination results verification in various international studies.

Through international cooperation, DORIS orbit determination technology can further improve the accuracy of satellite orbit determination to 5 cm. According to the above analysis, the radial accuracy of satellite precise orbit determination can reach 15 cm.

8.3.5.3 Error Source Analysis and Accuracy Control of Altimeter Instrument

The instrument error of altimeter can be categorized into fixed error and random error, where the fixed error can be corrected and the random error determines the measuring accuracy of altimeter instrument.

The main factors affecting the altimeter instrument error include tracking error, frequency accuracy, stability error, Doppler effect error, etc. Through the actual development level of altimeter, the altimeter instrument error of the satellite HY-2 can reach 4 cm.

8.3.5.4 Error Source Analysis and Precision Control of Transmission Path

1. The refraction in the dry tropospheric

The troposphere refers to the atmospheric bottom extending about 40 km upward from the Earth's surface, which contains about 90% of the atmospheric mass. When the electromagnetic wave signal passes through the atmosphere, the propagation path will bend due to the change of atmospheric refractive index, thus resulting in the error of the measured distance.

The tropospheric correction can be divided into dry component correction and wet component correction, which are related to water vapor content and other gases. The dry component correction can be expressed by the modeling of the ground air pressure measurements, while the wet component correction is usually processed and corrected by the onboard radiometer measurements. It must be noted that the dry component contains the weight of water molecules, while the wet component can explain additional information about the refractive index.

The dry component of atmospheric refraction is by far the largest correction, which must be taken into account in altimeter measurements. Smith and Weintraub (1953) expressed the dry gas correction as

$$N_{\text{dry}}(z) = \beta_{\text{dry}} P(z)/T(z), \quad (8.6)$$

where P represents atmospheric pressure (in mbar, 1 mbar = 100 Pa); T represents temperature (in K), and β_{dry} is an empirical parameter with $\beta_{\text{dry}} = 77.6 \text{ K/mbar}$.

Globally, sea surface atmospheric pressure generally ranges from 980 to 1035 mbar, so the mean global sea surface atmospheric pressure is about 1013 mbar. Many studies have shown that the estimation accuracy of sea surface atmospheric pressure can reach 5 mbar. According to the formula, the accuracy of dry tropospheric component can reach 1.14 cm.

2. Wet tropospheric refraction

Moist tropospheric distance correction includes water vapor correction and cloud liquid droplet correction. Based on the measurement of the size distribution of cloud liquid droplets over land, it is found that the refractive effect of cloud liquid droplets N_{liq} is almost linear with the density of liquid droplets, $\rho_{\text{liq}}(z)$, and N_{liq} can be expressed as

$$N_{\text{liq}}(z) = \beta_{\text{liq}} \rho_{\text{liq}}(z). \quad (8.7)$$

According to the expression of liquid water refractive index, the refractive distance of liquid water droplets along the signal propagation path is corrected as follows:

$$\Delta R_{\text{liq}} = 10^{-6} \int_0^R N_{\text{liq}}(z) dz = 1.6 L_z, \quad (8.8)$$

where L_z represents the integral of liquid water column along the propagation path, which is determined by the following formula:

$$L_z = \int_0^R \rho_{\text{liq}}(z) dz. \quad (8.9)$$

For T/P satellites, TMR can estimate the distance delay of the wet troposphere through measuring the brightness temperatures of 18 GHz, 21 GHz, and 37 GHz, thus avoiding the problem of what effective temperature T_{eff} is used. A two-step procedure is used for estimating ΔR_{vap} that a rough value is firstly estimated with a simple set of global coefficients; then a more precise value can be obtained with the coefficients in the vapor environment corresponding to the initial value. The purpose of the two-step treatment is to simulate different water vapors in mixing conditions.

In different geographic locations and under various weather conditions, the distance of T/P wet troposphere is corrected by about 1.1 cm according to the verification of air sounding device after T/P launch, even when there are huge clouds and wind in the radiometer footprint. The mean square deviation of the distance

correction is less than 1 cm by analyzing and comparing verifications on the four places.

For example, when the effective temperature is $T_{\text{eff}} = 270.6 \text{ K}$, $\beta'_{\text{vap}} = 6.36 \text{ cm}^3/\text{g}$ can be estimated according to the least square principle. In this case, when the global water vapor column varies from 0.5 to 7 g/cm², the path delay correction of wet tropospheric component ranges from 3 to 45 cm, and its standard deviation is 3 to 6 cm. According to the estimation of three-frequency passive microwave radiometer, the corresponding distance correction accuracy is about 1 cm, if the uncertainty of water vapor column estimation is 0.15 g/cm².

If the effect of liquid droplets in the cloud is not taken into account, and the L_z (L_z is generally less than 1.5 mm) is directly taken as the error estimate according to its calculation formula, then the error of liquid droplets is about 2.4 mm. Therefore, the error of wet tropospheric component is about 1.2 cm.

These calculations are carried out under certain assumptions and approximate conditions, and the actual accuracy should be less than this. If water vapor is measured by radiometer, the accuracy can be guaranteed at 1.2 cm.

3. Ionospheric refraction

For the ionospheric correction, the change of free electron content in the ionosphere shall be mainly considered when satellite signals propagate. Usually, the electron content varies from day to night (fewer free electrons at night) and from winter to summer (fewer electrons in summer), so it is a function of the solar cycle (less electron content when solar activity is weak). The signal delay is inversely proportional to the square of the altimeter monitoring frequency.

The ionospheric refraction effect of altimetry radar signal can be determined according to the dielectric characteristic of free electrons in the atmosphere described above. When the frequency is higher than 2 GHz, the Faraday rotation caused by the magnetism of the ionosphere can be neglected, and the real part of the ionospheric refractive index can be expressed in the form related to the electromagnetic radiation frequency f_p :

$$\eta_{\text{ion}} = \left(1 - \frac{f_p^2}{f^2}\right)^{1/2}, \quad (8.10)$$

where f_p represents the natural frequency of electrons vibrating in the plasma region. The relation between plasma frequency and electron density is $f_p^2 = 80.6 \times 10^6 n_e$, where the unit of n_e is electron number/cm³. Generally, in the daytime, the ionospheric height at 250–400 km in the mid-latitude region has the highest electron density, $n_e \approx 10^6$ electron number/cm³, and the corresponding plasma frequency is $f_p \approx 9 \text{ MHz}$. When the electromagnetic frequency is less than f_p , the ionospheric refractive index becomes imaginary, implying that the electromagnetic signal is reflected by the ionosphere, because the signal cannot propagate under the real imaginary refractive index condition.

The Ku band and C band frequencies of T/P dual-frequency altimeter are 13.6 GHz and 5.3 GHz, respectively. Their magnitudes are three orders of magnitude of plasma frequency f_p . For altimeter applications, the above formula can be expanded into binomials:

$$\eta_{\text{ion}} \approx 1 - \frac{f_p^2}{2f^2} = 1 - \frac{40.3 \times 10^6 n_e}{f^2}. \quad (8.11)$$

Unlike the nondispersive nature of tropospheric gases, it is clear that η_{ion} depends on frequency, so the ionosphere is a dispersive medium. In fact, η_{ion} is less than 1, so the propagation speed $c_p = c/\eta_{\text{ion}}$ is greater than that in vacuum.

There are two models mainly used in ionospheric correction: NASA model and Jet Propulsion Laboratory (JPL) model. NASA model is an empirical model for global ionospheric correction. During the peak period of solar activity, the model error reaches 4 cm, however, at other times, the mean square error is 1–2 cm, and the night correction error is close to zero. JPL model, also called Faraday rotation model, measures the Faraday rotation of satellite in ground station, and then converts this observation value into integral electron density along the slant distance direction of satellite. Finally, by interpolating the observations of these individual ground stations, the electron density in other parts of the world can be calculated. This electron density is a function of time, satellite geomagnetic latitude, and local solar zenith angle. The model is used in the satellite Seasat.

The electron density N_e is a function of the solar cycle, which varies from day to night and from summer to winter. Normally, variation of electron density at night is small, and electron density is minimal in summer and when solar activity is at the least frequent. According to the estimation, the value of electron density N_e varies from 10^{16} to 10^{18} , mainly depending on the observation time. For the signal frequencies used by satellites, the ionospheric correction in Ku band can be calculated, and is between 0.2 and 23 cm, while the C band correction is larger, between 1.5 and 150 cm. In the altimetry, the Ku band is mainly used as the distance measurement, while the other bands are used for check. Therefore, the satellite ionospheric error is between 0.2 and 23 cm.

If a dual-frequency altimeter is used, for example, the T/P satellite uses a dual-frequency microwave instrument, and the Ku band and C band frequencies are 13.6 GHz and 5.3 GHz, respectively. It is generally assumed that the two signal paths are identical and therefore the electron content is equal. Let h_0 be the actual height of the satellite, h_{Ku} and h_{C} are the heights measured within the Ku and C bands, respectively, then

$$h_{\text{Ku}} = h_0 + 40.3 \frac{N_e}{f_{\text{Ku}}^2}, \quad (8.12)$$

$$h_{\text{C}} = h_0 + 40.3 \frac{N_e}{f_{\text{C}}^2}. \quad (8.13)$$

Thus the corrected satellite altitude is

$$h_0 = \frac{f_{Ku}^2 h_{Ku} - f_C^2 h_C}{f_{Ku}^2 - f_C^2}. \quad (8.14)$$

Therefore, the use of a dual-frequency altimeter can attenuate the effects of most ionospheric refractions.

The ionospheric single frequency range correction formula is obtained as follows:

$$\Delta R_{\text{ion}} = \frac{40.3}{f^2} N_{\text{TECU}}. \quad (8.15)$$

The differential equation is

$$d\Delta R_{\text{ion}} = \frac{40.3}{f^2} dN_{\text{TECU}}. \quad (8.16)$$

According to the launched altimetry satellites and related research, the ionospheric correction accuracy can generally reach 3 cm. If the dual-frequency altimeter is used, the two signal paths are identical, so the electronic content is equal. Theoretically, the ionospheric effect can be eliminated. However, considering the objective conditions, the error cannot be completely eliminated. According to the results of the T/P research, with the dual-frequency altimeter, the accuracy of the satellite ionospheric correction can reach T/P accuracy, about 1.3 cm, and can be also appropriately expanded to 2 cm.

8.3.5.5 Analysis of Sea State Error Source and Precision Control

The return signal measured by the altimeter is the pulse signal reflected by the wavelet reflection surface within the antenna footprint. Therefore, the echo shape can be determined by the altitude distribution of these specular reflectors, rather than by the actual sea-level altitude distribution in the radar antenna footprint. Because of the difference between reflector distribution and sea surface height, such deviation correction must be taken into account when estimating the mean sea surface height. The distance from the satellite to the sea surface is determined by the interval between the pulse transmission time and the time of the midpoint of the front of the received return waveform. The half-power point corresponds to the central height of the mirror scatterer, which is called the Electromagnetic (EM) sea surface. The difference between the electromagnetic sea surface and the mean sea surface estimated by the airborne tracking algorithm from the average return waveform has two factors: one is the electromagnetic deviation, and the other is the slant deviation.

1. Electromagnetic deviation

The physical principle of electromagnetic deviation is easy to establish, which is caused by that the reflection power of the trough on each unit reflector is greater than that of the peak, because the backscattering power reflected from the reflection surface of the wavelet is proportional to the curvature radius of the longwave part of the spectrum to some extent. If the sea surface height is non-Gaussian distribution, the ocean waves are usually inclined, so that the curvature radius of the trough is larger than that of the peak. As a result, the backscattering power tends to approach the trough and causes deviation. When there is a strong wind on the sea surface, there is a small-scale surface roughness near the wave crest, which makes the reflected pulse signal in all directions rather than in the incident direction. In this case, even if there is no slant deviation in the elevation distribution, its electromagnetic deviation will be further enhanced. Therefore, the trough of backscattering power measured by the altimeter is larger than the peak, and the electromagnetic deviation is biased toward the trough.

Historically, electromagnetic deviation, as a function of effective wave height, is defined as $1/3$ of the maximum wave height in the field of view (expressed as $H_{1/3}$), which is generally considered to be equivalent to 4 times the standard deviation of sea surface height. Early studies have shown that with the increase of wave height, the electromagnetic deviation increases monotonously, so the empirical expression of electromagnetic deviation is as follows:

$$\Delta R_{EM} = -bH_{1/3}, \quad (8.17)$$

where B is a measure with a dimension of 1 and equivalent to the electromagnetic deviation normalized by $H_{1/3}$. In fact, electromagnetic deviation also depends on other characteristics of wave field, and $H_{1/3}$ is only one of them. It can be obtained directly from altimeter waveform, and it is unique and unambiguous. The coefficient b is called the sea state deviation coefficient.

$$b = a_0 + a_1U + a_2U^2 + a_3H_{1/3}. \quad (8.18)$$

The four-parameter model is better than the three-parameter model in explaining the increase of sea surface high variance by about 1 cm^2 , when the effective wave height $H_{1/3}$ changes most is the largest in middle and high latitudes, but there is no obvious and direct discrimination improvement in low latitudes.

2. Slant deviation

The slant deviation is the elevation difference between the average scattering surface and the center of the reflecting surface. The center of the reflector corresponds to the two-way propagation time at the half-power point at the front of the return waveform. The slant deviation can be approximated by the following formula:

$$\Delta R_{\text{skew}} = -\lambda_{\zeta} \frac{H_{1/3}}{24}, \quad (8.19)$$

where λ_{ζ} is elevation slant. If the wave height is 2 m and the inclination is 0.1, the corresponding distance is corrected to 0.8 cm. If the wave height reaches the limit value of 10 m, the error increases to 4 cm.

In general, the standard deviation of effective wave height is between 0.5 and 1.5 m (7-year data calculation). When $d\Delta R_{\text{EM}} \approx -0.02dH_{1/3}$ is chosen, the corresponding electromagnetic deviation accuracy is between 1 and 3 cm. If the inclination deviation is considered, the accuracy is less than 3 cm.

8.3.5.6 Analysis and Estimation of Orbit, Instrument, and Environmental Errors

Satellite altimetry observations are objectively affected by many factors, whose correction must be taken into account in practical applications. Table 8.6 shows the correction of various errors in some satellite altimetry that have been launched. Satellite altimetry accuracy is mainly assigned and calculated for some influential factors, which can be used to analyze the error of satellite altimetry according to the experience of these satellites.

8.3.5.7 Analysis of Other Error Sources

Other errors mainly include the errors caused by the platform pointing deviation, the coordinate system transformation, the geoid model, or the ground correction method.

The research by NASA's World Ocean Circulation Experiment (WOCE) shows that the height measurement error of 2 cm will be introduced for the platform pointing error of 0.2° , if it is not corrected (Altimeter Algorithm Workshop. *U.S. WOCE Technical Report*. Number 2, November 1988, P28).

Research shows that the error caused by the deviation of the platform pointing or by the coordinate system conversion or by the geoid model as well as by the ground correction method will lead to an altimetry error of about 4 cm.

8.3.5.8 Data-Adjustment Post-Processing and Accuracy Improvement

The data post-processing of altimeter can improve the quality of data and meet the accuracy requirements of related disciplines on altimetry data. Crossover adjustment plays an important role in satellite altimetry data processing. The usual method is to use the difference between the rising and falling sea surface heights of crossover point to solve the radial orbit errors (Liang, 1983; Van Gysen, H., 1997), and then to study the corrected sea surface heights. The starting point is that the discrepancy of crossover point, i.e., the difference of sea surface height between ascending and

Table 8.6 Correction of main errors in satellite altimetry

Major errors		Seasat	Geosat	ERS-1	Topex/Poseidon
Instrumental error	Instrument noise/cm	10	5	3	<2
	Instrument deviation/cm	7	5	3–5	2
	Clock skew/ms	5	3–5	1–2	<1
	Total error/cm	15	7	5	2
Environmental error	EM deviation/cm	5	2	2	<2
	Waveform distortion/cm	1	1	1	1
	Dry troposphere/cm	2	1	1	1
	Wet troposphere/cm	2	1	1	1
	Ionosphere/cm	2–3	2–3	2–3	1.3
	Total error/cm	10	6	4	3.5
Orbital error	Field of gravity/cm	25	15	15	<2
	Radiation pressure/cm	15	10	6	<2
	Atmospheric drag/cm	15	10	6	<2
	GM constant/cm	–	–	2	1
	Tide/cm	12	5	5	<2
	Troposphere/cm	5	4	2	1
	Station position/cm	10	5	3	1
Total root mean square error/cm		33	22	19	<5

descending arcs measured at crossover point ΔSSH , is a typical reflection of satellite radial orbit error in altimetry observations. The errors caused by the satellite radial orbit error and sea surface time-varying residuals as well as the influence of systematic error on altimetry data can be weakened (Van GysenH, 1997; Kim, 1997), and the accuracy of altimetry can be increased by 2–3 times through finding crossover point and crossover adjustment.

8.3.5.9 Summary of Error Analysis

Based on the above comprehensive analysis, according to research on other factors, the ionospheric calibration error, the atmospheric calibration error, the sea condition

factor, and empirical value error can be reduced to 2 cm by the radar altimeter with the dual-frequency technology, 2 cm by the radiometer with three-frequency calibration, 4 cm and 4 cm, respectively. Considering the existing precision orbit determination methods and the development level of altimeter in China, the allocated error values are specified for the precision orbit determination error up to 15 cm and altimeter instrument error up to 4 cm.

The total root mean square error is specified for the above error sources up to 16.76 cm. Since the accuracy of measurement can be increased by 2–3 times by crossover adjustment, the total accuracy is specified for measurement after post-processing up to 8.4 cm.

8.4 Design and Analysis of Microwave Scatterometer

As an important payload of ocean microwave remote sensing satellite, microwave scatterometer is characterized by large scale, all-time, and global observation in wind field observation, and plays a special role in typhoon monitoring. The microwave scatterometer monitors the typhoon's moving path and identifies the typhoon's center by observing the sea surface wind field. The microwave scatterometer can be used to detect the typhoon center by extracting the wind speed and direction of the regional wind field.

8.4.1 Principle of Scatterometer

A microwave scatterometer is a sort of calibrated radar for measuring the backscattering coefficient σ_0 of an extended surface target. The radar measures the radar backscattering coefficient by emitting radiofrequency pulses and measuring the backscattering power. According to the radar range equation, σ_0 can be obtained through ground processing. At present, ocean application is the main application field of the scatterometer. Because of the dependence of σ_0 on the wind speed and direction of sea surface, the inversion of wind vector of sea surface is performed according to the model by measuring σ_0 of multiple azimuths of the same radar resolution unit. Scatterometer can be used to measure soil moisture, precipitation, vegetation, and crop growth. Scatterometer covers a certain amount of ground swath by rotating of pencil beam around the nadir direction with a fixed incidence elevation angle in the motion of satellite platform along the orbit. The observation schematic diagram is shown in Fig. 8.5.

The microwave transmitter is connected to the antenna through the duplexer and transmits radiofrequency pulses to the sea surface. After the sea surface echo is received by the antenna, it is sent to the receiver via the duplexer, and then recovered by the receiver into a video signal and finally sent to the signal processor. The internal calibration device couples part of the power of the transmitter to the receiver to form

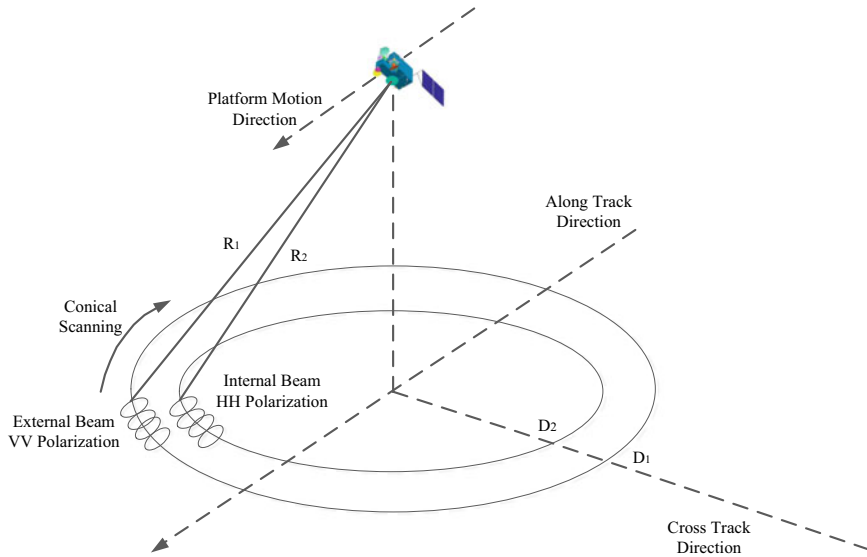


Fig. 8.5 Sketch of scatterometer observation

a closed loop, so as to achieve internal calibration and eliminate measurement errors caused by changes in the transceiver system. The signal processor processes the echo signal, the internal calibration signal, and the pure-noise signal without echo to obtain a normalized radar backscatter coefficient σ_0 of the sea surface scattering source. The ground processing system inverts the sea surface wind speed and wind direction through a certain mathematical model for σ_0 of different incident angles, azimuths, and antenna beams.

8.4.2 Scatterometer Design Analysis

As an important payload of satellite, microwave scatterometer mainly completes the measurement of sea surface wind field and other tasks. The functions of the microwave scatterometer are as follows:

1. Measuring the sea surface wind field by measuring the scattering coefficient σ_0 of the extended surface target.
2. Wind direction and wind speed are measured by using the anisotropy of microwave scattering from sea surface wind field.
3. The sea surface wind vector is inversed from the model by measuring the σ_0 of multiple azimuths of the radar resolution unit.
4. The inversion accuracy of wind field should be improved by conical scanning dual-beam system.
5. The drift of the instrument is corrected in an internal calibration mode.

8.4.2.1 Measurement and Inversion of Atmospheric Wind Speed and Direction at Sea Surface

The reason why the scatterometer can be used to measure the sea surface wind field is the anisotropic characteristics of the sea surface wind field. In other words, when the incident angle is constant, the backscattering coefficient varies with the azimuth angle (the angle between the incident surface of electromagnetic wave and the wind direction). For example, when the azimuth angle is 0° , that is, σ_0 is the maximum by the adverse wind. When the azimuth angle is 180° , that is, σ_0 is the second largest by downwind. When the azimuth angle is 90° , that is, σ_0 is the minimum by crosswind. The azimuth modulation characteristic of the sea surface wind direction approximates to the cosine function.

In the design of wind field inversion algorithm for spaceborne scatterometer, the most important thing is to ensure the uniqueness of wind field inversion as far as possible. Because of the unavoidable noise effect in the actual measurement process, the curves calculated according to the measurement results cannot ideally intersect at one point, and may be a small area. Therefore, the maximum likelihood estimation technique should be used in the algorithm design for the unique wind field inversion. On the other hand, the continuous variation of sea surface wind field can be utilized in the wind field inversion, and the fuzzy solution can be eliminated by referring to each other in the wind field inversion of adjacent surface elements.

8.4.2.2 Analysis and Determination of Key Technical Indicators

The microwave scatterometer usually works in the Ku or C frequency band, and uses the pen-shaped cone scanning method to measure the scattering coefficient σ_0 of the sea surface expansion target. It adopts the dual-feed, dual-beam, and dual-polarization modes, and supports the internal calibration mode to correct the drift of the instrument. According to the user's application requirements and the processing of system data, the microwave scatterometer shall usually satisfy the wind speed measurement accuracy better than 2 m/s in the wind speed range of 2–4 m/s, and the wind direction measurement accuracy shall be better than 20° according to the observation requirements of the sea surface wind field, the typhoon moving path and the center.

The key design elements of scatterometer include the following:

1. **Launch frequency** depends on ITU, detection target, engineering achievable, and EMC requirements of the whole satellite.
2. **Measurement range of backscattering coefficient** mainly depends on the dynamic range and SNR of the system.
3. **Wind speed measurement range and accuracy** mainly depends on the dynamic range of the system and the accuracy of the inversion model.
4. **Wind direction measurement accuracy** mainly depends on the dynamic range of the system and the accuracy of the inversion model.

5. **Transmitting pulse power** mainly depends on the required measurement accuracy and engineering achievable requirements.
6. **Polarization mode** mainly depends on the observation target.
7. **Antenna gain** depends on the transmission power of the system and the required measurement accuracy;
8. **Beamwidth and ground footprint** depends on the user's observation elements.
9. **Observation angle** depends on the orbital height, swath, and wind field measurement requirements.

8.4.3 Configuration and Topology of Microwave Scatterometer

Microwave scatterometer is an active microwave remote sensor, which is specially used to measure the scattering characteristics of ground objects—the backscattering coefficient σ_0 . The block diagram of the microwave scatterometer is shown in Fig. 8.6.

The basic operating process of the microwave scatterometer is that the microwave transmitter is connected with the antenna through a duplexer, and transmits radiofrequency pulses to the sea surface. The pulse signal is scattered through the target. After the scattered echo signal is received by the antenna, it is sent to the receiver by a duplexer, and then restored to a video signal by receiving and processing, and finally sent to the signal processor. The internal calibration device couples part of the transmitter power to the receiver to form a closed loop, so as to achieve internal calibration and eliminate the measurement errors caused by any changes in

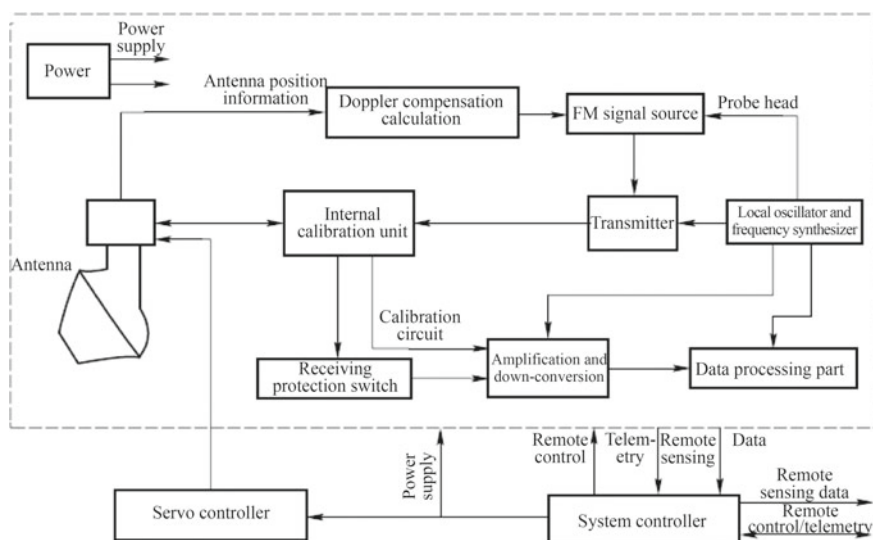


Fig. 8.6 Composition block diagram of scatterometer

the transceiver system. The signal processor processes the echo signal, the internal calibration signal, and the pure noise signal without echo to obtain the normalized radar backscattering coefficient σ_0 of the sea surface scattering source. The ground processing system then calculates the sea surface wind speed and direction through a certain mathematical model based on σ_0 measured at different incident angles, different azimuths, and different antenna beams.

The satellite microwave scatterometer is composed of three satellite-mounted single units: detection head, servo controller, and system controller. The detection head includes an antenna, a scanning mechanism, and a high-frequency box. The scanning mechanism is composed of motor, resolver, precise conductive sliding ring, bearing, and other components. The high-frequency box is equipped with radar transmitter, power amplifier, receiver, frequency synthesizer, data processor, microwave front end, and system distribution unit.

1. The waveguide slot array antenna is used as the scatterometer antenna, which mainly consists of antenna radiation array, radiation waveguide, feed waveguide, and feed power division network to transmit and receive microwave signals.
2. The traveling wave tube amplifier is used as the power amplifier unit, including traveling wave tube and power supply. Its main function is to amplify the microwave signal.
3. Radar transmitter adopts secondary down-conversion scheme, which mainly consists of mixer, amplifier, filter and secondary power supply. Radar receiver adopts secondary down-conversion scheme and Automatic Gain Control (AGC). It is mainly composed of mixer, amplifier, filter, CNC attenuator, and power supply.
4. The microwave front end adopts the nondelay internal calibration method with the advantages of simple circuit, good stability, high calibration accuracy, high requirements on isolation of the calibration unit, and high system electromagnetic compatibility. The internal calibration unit consists of directional coupler, microwave switch, attenuator, etc.
5. The scanning servo unit adopts high-performance fully digital permanent magnet synchronous AC servo system, which requires the motor to directly drive load. It is characterized by large output torque and small torque fluctuation. The servo control system with fast response and good steady state is composed of a torque motor, angle encoder (resolver), bearing, servo drive circuit, servo control circuit, and the corresponding fixed parts.
6. The signal processing unit consists of a system controller, a data processor, and a signal generator. The main functions of the system controller are the generation of radar working sequence, the reception and transmission of telemetry and remote control signal, and the communication with satellite. The data processor completes the adoption and processing of echo signals and the generation of remote sensing data. The signal generator generates the linear frequency modulation pulse signal of radar.

7. The function of frequency synthesizer is to generate various high stability reference signals, including RF local oscillator signal, IF local oscillator signal, A/D sampling clock, clock reference signal, etc. These signals are supplied to the DDS signal source, radar transceiver channel, data processor, and radar timer as frequency reference and time reference signals.
8. The distribution unit of the system consists of DC/DC conversion circuit, instruction execution circuit, and TT&C circuit. The DC/DC conversion unit provides secondary power supply to each unit. The instruction execution unit completes the execution of direct and indirect instructions, realizes the distribution of primary power supply and the switching between main and standby power supply. The TT&C unit performs the separation and driving of the indirect remote command and the sampling of the telemetry.
9. The system controller completes the control of the operating state of the microwave scatterometer and exchanges remote sensing, telemetry, and remote control information.
10. The locking device completes the locking of the detecting head during the launch to ensure a rigid connection between the components of the antenna. After the satellite gets into orbit, the screw is cut by the pyrotechnic cutter to release the constraint between the high-frequency box and the mounting plate.

8.4.4 Design of Operating Mode

8.4.4.1 Normal Operating Mode

During the orbital period, the microwave scatterometer is always in operating state and transmits the acquired remote sensing data to the ground station through the data transmission subsystem. By the internal calibration, the microwave scatterometer corrects the drift of the instrument and transmits the calibration data to the ground station through the data transmission subsystem.

There are three operating modes in the normal on-orbit operating mode: wind measurement mode, internal calibration mode, and original data storage mode.

The wind measurement is the main operating state of the scatterometer. The internal and external beams measure the radar backscattering coefficient of the sea surface echo target at different polarizations and different incident angles.

The internal calibration can realize the internal calibration of the scatterometer instrument and eliminate the measurement error caused by the change of the transceiver channel system. In the wind measurement mode, two internal calibration tests are carried out within one lap of the scatterometer scanning. In the internal calibration mode, the microwave scatterometer adopts continuous calibration to eliminate the measurement errors in the system, especially errors in the receiver at different gains.

In the original data storage mode, the sea surface echo signal is sampled and directly downloaded by the radar instead of the processing to test the radar data processor function and obtain the raw data for other applications.

8.4.4.2 Emergency Mode

When the subsystem fails, the self-protection function should be available for avoiding interference with other subsystems. If the scatterometer antenna is required to stop, the antenna can be slowed down and stopped by shutting down.

8.4.5 Accuracy Analysis and Precision Control of Microwave Scatterometer

Microwave scatterometer is a radar system that quantitatively measures the target backscattering coefficient. The measurement accuracy of the backscattering coefficient directly affects the inversion accuracy of wind vector. The measurement errors of the radar backscattering coefficient mainly come from the measurement accuracy of echo signal, the internal calibration accuracy, and the influence of antenna beam pointing deviation.

8.4.5.1 Analysis and Control of Measuring Accuracy of Echo Signal

In the design of the microwave scatterometer system, the accuracy of echo measurement is generally evaluated by measuring the relative standard deviation K_p . The measurement accuracy of echo signal mainly depends on the number of independent samples and the SNR of data processing signals.

$$K_p = \sqrt{\frac{(1 + 1/S_n)^2 + (1/S_n)^2}{N}}. \quad (8.20)$$

The SNR of the microwave scatterometer is specified at 6 dB when processing the echo signal. The acquisition of independent sampling number includes the number of repeated observations in the same resolution unit and the number of independent sampling in the range direction obtained by using range filtering technology. According to the design of microwave scatterometer system (double-point beam scanning observation) and the overlap of adjacent resolution units about 1/3, the repeated observation times of the same resolution unit are more than 4, and is specified at 4 in the calculation.

For example, if the transmitting signal of the microwave scatterometer is designed as a linear frequency modulation signal, and the bandwidth of the linear frequency

modulation signal is 5 MHz, the pulse width T_P is 1.5 ms, and the bandwidth B_S after receiving the de-linear frequency modulation is 640 kHz, then the independent sampling number N_R is obtained as

$$N_R = T_P \cdot B_S = 960. \quad (8.21)$$

Then, the total number of independent samples of the system is approximately $N = 4 \times 960 = 3840$.

$$K_P = 1/\sqrt{N} = 1/\sqrt{3840} = 0.01613(0.07dB). \quad (8.22)$$

Considering that the amplitude and phase of the receiving channel will affect the data processing, the measurement accuracy of backscattering coefficient will be better than 0.14 dB.

8.4.5.2 Analysis and Control of Internal Calibration Accuracy

The main function of the internal calibration loop of microwave scatterometer is to realize the relative measurement of the gain variation of radar transceiver channel, so as to provide the relative calibration data for system correction and system error compensation, thus eliminating the measurement error caused by the instrument itself.

In the design, the microwave scatterometer system adopts an internal calibration scheme based on the nondelay ratio method, which requires that the isolation between the transmitting channel and the receiving channel be more than 130 dB.

In order to effectively eliminate the measurement error caused by the change of the parameters of the transceiver channel, the internal calibration of the system shall theoretically be as frequent as possible, the high stability of the system is required during two calibration processes. Based on the working characteristics of the microwave scatterometer, two calibrations are designed in a scanning period. The internal calibration is realized on both sides of the observation swath. The internal and external beams are measured three times at each calibration, thus improving the calibration accuracy.

According to the test results in the pre-research stage, the measurement accuracy of the internal calibration can be better than 0.15 dB.

8.4.5.3 Analysis and Control of Measurement Accuracy of Influencing Factors Such as Antenna Beam Pointing Accuracy

During the on-orbit operation of the microwave scatterometer, the attitude change of the satellite platform will cause the change of the antenna beam direction, the size of the ground footprint, and the echo power, thus affecting the measurement accuracy of the backscattering coefficient. The on-orbit data processing of microwave

scatterometer worldwide shows that the attitude error is the main relative error source. The pointing direction of the scatterometer antenna will shift when the attitude of the satellite changes. If the offset cannot be corrected during data processing, an error will be introduced into the calculation of σ_0 . According to the analysis of on-orbit measurement data of microwave scatterometer worldwide, if the measurement accuracy of antenna beam pointing reaches 0.03° and other unpredictable errors are taken into account, the measurement accuracy of target backscattering coefficient will be better than 0.2 dB.

8.4.5.4 Calibration Accuracy Allocation

After analyzing and controlling, the accuracy values of the echo signal, the internal calibration accuracy, and other influencing factors can reach at 0.14 dB, 0.15 dB, and about 0.2 dB, respectively. The measurement accuracy value of the backscattering coefficient by the microwave scatterometer system is better than 0.49 dB.

8.5 Design and Analysis of Microwave Radiometer

As an important payload of ocean microwave remote sensing satellite, the main task of microwave radiometer is to acquire ocean surface and ice data, measure atmospheric water vapor content, cloud water content, and rainfall.

8.5.1 Principle of Microwave Radiometer

The theoretical basis of microwave radiation measurement is Planck's law, that is, all objects with a temperature above absolute zero emit energy in the form of electromagnetic radiation at all frequencies. The radiation value is related to the temperature and properties of the object. This is the basic definition of Planck's law, whose mathematical expression is shown as follows:

$$I = \mu \varepsilon \frac{h f^3}{e^{h f / k T} - 1}, \quad (8.23)$$

where I is the unit radiation intensity in $\text{W m}^{-2} \text{Hz}^{-1} \text{sr}^{-1}$, h is the Planck constant ($6.6256 \times 10^{-34} \text{J s}$), k is the Boltzmann constant ($1.38 \times 10^{-23} \text{J K}^{-1}$), and T is the object physical temperature. Under the Rayleigh–Jeans approximation condition ($h f / (k T) \ll 1$), for a medium with a permeability μ and a dielectric constant ε , I is

$$I = \frac{k T}{\lambda^2} \frac{\mu \varepsilon}{\mu_0 \varepsilon_0}, \quad (8.24)$$

where λ is the wavelength in free space. In free space, I can be obtained by the following formula:

$$I = \frac{kT}{\lambda^2}. \quad (8.25)$$

In microwave band, Rayleigh–Jeans approximation condition can be well satisfied, so Rayleigh–Jeans law can be applied in microwave field.

The black body is an ideal radiator. The emission of all objects in nature is weaker than that of the black body at the same temperature. The unit radiation intensity I of an object is a function of the radiation direction and polarization. In passive remote sensing, the radiometer receives the unit radiation intensity $I_\beta(\theta, \phi)$ emitted by the observed object, which is called equivalent radiation temperature of brightness temperature $T_{\beta B}(\theta, \phi)$ and defined as

$$T_{\beta B}(\theta, \phi) = I_\beta(\theta, \phi) \frac{\lambda^2}{k}. \quad (8.26)$$

If the object has a uniform physical temperature T , the emissivity $e_\beta(\theta, \phi)$ of the object is defined as

$$e_\beta(\theta, \phi) = \frac{T_{\beta B}(\theta, \phi)}{T}, \quad (8.27)$$

where the emissivity e is related to surface roughness, temperature, frequency, polarization mode, and dielectric constant.

8.5.2 Calculations of Microwave Radiometer Temperature Measurement

The energy received by the antenna comes from the whole 4π solid angle and has a brightness distribution $B_i(\theta, \phi)$. The apparent temperature T_{AP} of the antenna can be defined by the definition method of the object brightness temperature.

$$B_i(\theta, \phi) = \frac{2k}{\lambda^2} T_{AP}(\theta, \phi) \Delta f. \quad (8.28)$$

Then the power received by the antenna is

$$P = \frac{1}{2} A_{eff} \iint_{4\pi} \frac{2k}{\lambda^2} T_{AP}(\theta, \phi) \Delta f F_n(\theta, \phi) d\Omega, \quad (8.29)$$

where p is the power that the antenna provides to the receiver. Assuming that an equivalent temperature, a bandwidth an effective area of the antenna and a noise power provided by the resistor are at this temperature are T_A , Δf , A_{eff} , and p , respectively, then

$$p_n = kT_A \Delta f = p. \quad (8.30)$$

Combining the above formulas, we can get

$$T_A = \frac{A_{\text{eff}}}{\lambda^2} \iint_{4\pi} T_{AP}(\theta, \varphi) F_n(\theta, \varphi) d\Omega. \quad (8.31)$$

Let T_A be the antenna radiation measuring temperature, the above formula can also be expressed as follows:

$$T_A = \frac{\iint_{4\pi} T_{AP}(\theta, \varphi) F_n(\theta, \varphi) d\Omega}{\iint_{4\pi} F_n(\theta, \varphi) d\Omega}. \quad (8.32)$$

That is, T_A is equal to the apparent temperature distribution integrated by the antenna weighting function $F_n(\theta, \varphi)$ at a 4π solid angle, and normalized by the integral of the weighting function. The above formula can also be divided into two parts, one part representing the contribution of the main lobe and the other part representing the contribution of each direction (side lobe) except the main lobe:

$$T_A = \frac{\iint_{ML} T_{AP}(\theta, \varphi) F_n(\theta, \varphi) d\Omega}{\iint_{4\pi} F_n(\theta, \varphi) d\Omega} + \frac{\iint_{4\pi-ML} T_{AP}(\theta, \varphi) F_n(\theta, \varphi) d\Omega}{\iint_{4\pi} F_n(\theta, \varphi) d\Omega}. \quad (8.33)$$

According to the definition of main lobe efficiency η_M , effective apparent temperature T_{ML} of main lobe contribution and effective apparent temperature T_{SL} of side lobe contribution, the above formula can be converted into the following forms:

$$T_A = \eta_M T_{ML} + (1 - \eta_M) T_{SL}. \quad (8.34)$$

The above formula is derived under the assumption that the antenna is lossless ($\eta_l = 1$). If the radiation efficiency of the antenna is η_l , then

$$T'_A = \eta_l \eta_M T_{ML} + \eta_l (1 - \eta_M) T_{SL} + (1 - \eta_l) T_0, \quad (8.35)$$

where T'_A is the measured value of the microwave radiometer, depending mainly on the contribution of the main beam T_{ML} . If η_l , η_M , T_{SL} , and T_0 are known, T_{ML} can be easily obtained from T'_A .

Square law detection is used in the microwave radiometer system to make the input power of the radiometer linear with the output voltage, that is,

$$V = aT'_A + b, \quad (8.36)$$

where a and b are two calibration constants, and the specific values of a and b can be determined by two-point calibration.

The microwave radiometer converts the RF input noise power into a proportional output voltage V_{OUT} , and the relation is

$$V_{OUT} = g_{LF} C_d G k T_{SYS} B = G_s T_{SYS}, \quad (8.37)$$

$$G_s = g_{LF} C_d G k B, \quad (8.38)$$

$$T_{SYS} = T_A + T_{REC}, \quad (8.39)$$

where g_{LF} is the voltage gain of low-pass filter, C_d is the power sensitivity constant of square-law geophone, T_{SYS} is the system noise temperature, T_A is the output noise temperature of antenna, T_{REC} is the effective local noise temperature of receiver, V_{OUT} is the output voltage of microwave radiometer, G_s is the gain factor of system.

It can be seen from the above equation that there are two uncertain constants in the equation of the output voltage of the microwave radiometer and the input noise temperature, namely, the system gain factor G_s and the effective local noise T_{REC} , both of which can be determined by microwave radiometer calibration..

Based on the previous analysis, the output voltage of the microwave radiometer is affected by system gain G and effective local noise T_{REC} , which are related to active devices such as amplifiers or mixers and fluctuate with the change of physical temperature of power supply and devices. The sensitivity of the microwave radiometer is defined as the magnitude of the input signal power corresponding to the output voltage fluctuation (1σ) caused by the system noise. The sensitivity formula of the full-power microwave radiometer is as follows:

$$\Delta T_N = \frac{T_{SYS}}{\sqrt{B \tau}}. \quad (8.40)$$

The uncertainty of microwave radiometer measurement is not only caused by the effective local noise of the system, but also by the gain fluctuation of the receiver. Because V_{OUT} has a linear relationship with the product $G_s T_{SYS}$, the output is mistaken for T_{SYS} to increase $\Delta T_{SYS} = T_{SYS} (\Delta G_s / G_s)$ if the system gain G_s increases ΔG_s .

Statistically, the stability of the microwave radiometer is the uncertainty of the root mean square of T_A caused by the change of system gain.

$$\Delta T_G = T_{SYS} \left(\frac{\Delta G_s}{G_s} \right), \quad (8.41)$$

where G_s is the system gain factor and ΔG_s is the gain factor fluctuation.

Since the uncertainty caused by noise ΔT_N and the uncertainty caused by the gain ΔT_G are statistically independent, the minimum detectable signal of the microwave radiometer, i.e., the total RMS uncertainty, can be expressed as

$$\begin{aligned}\Delta T_{\min} &= [(\Delta T_N)^2 + (\Delta T_G)^2]^{1/2} \\ &= T_{\text{SYS}} \left[\frac{1}{B \tau} + \left(\frac{\Delta G_S}{G_S} \right)^2 \right]^{1/2}.\end{aligned}\quad (8.42)$$

The above expression determines the minimum detectable signal of the radiation measurement of the full-power microwave radiometer, which takes into account the effects of both noise and gain variations.

8.5.3 Design and Analysis of Microwave Radiometer

The microwave radiometer has the following functions:

1. the sea surface temperature can be obtained by measuring the microwave brightness temperature of the sea surface;
2. the brightness temperature of bubbles related to large storms or hurricanes can be measured, so that the wind speed can be inverted;
3. the conical scanning method is adopted; and
4. the internal calibration mode is used to correct the drift of the instrument.

The sea surface temperature can be obtained by measuring the microwave brightness temperature of the sea surface by multi-polarization measurement in C, X, K, and Ka bands. The microwave radiometer can also measure the foam brightness temperature related to the large storm or hurricane, so that the wind speed up to 50 m/s can be inverted. The dynamic range of microwave radiometer is generally from 3 to 350 K according to the requirements of ocean dynamic environment detection and application, which supports the internal calibration mode less than 1 K and corrects the drift of the instrument. The following factors are listed for the analysis of the main indicators of microwave radiometers:

- (1) **The central frequency and bandwidth of the observation channel** are mainly selected according to the constraints of observation elements and ITU, as well as the requirements of the whole satellite EMC.
- (2) **The measurement range and accuracy of sea surface temperature** mainly depend on the system correction accuracy, SNR, dynamic range, etc.
- (3) **Scanning form of antenna** are mainly selected according to the difficulty of system implementation, the swath requirement, and the requirement of incident angle for different observation elements.

8.5.4 Configuration and Topology of Microwave Radiometer

The connection block diagram of the working principle of the microwave radiometer is shown in Fig. 8.7. The microwave radiometer is divided into four parts according to its structure, namely the radiometer detection head (including locking device), the integrated processor, the servo controller, and the calibration source controller. The detection head includes an antenna, a scanning mechanism and a high-frequency box. The scanning mechanism consists of a motor, a resolver, a precise conductive sliding ring, bearing, and other components. The scanning mechanism is equipped with a cold air mirror and a thermal calibration source. The high-frequency box is equipped with a feeder and its network, receiver, information acquisition circuit, and control and distribution circuit.

The satellite microwave radiometer has 5 frequency points and 9 receiving channels. In addition to channel K2, each frequency and polarization has its own receiving channel.

The operating process of microwave radiometer is as follows: firstly, the antenna conically scans by the servo circuit driven scanning mechanism for, the ground observation and calibration in each rotation cycle; secondly, the signal received by the antenna is separated in the feed network by frequency and polarization, which are sent to the information acquisition unit for information acquisition after low noise amplification, filtering, square-law detection, and low-frequency amplification; finally, the collected remote sensing data are received and processed in the integrated processor, the channel control parameters are given, gain control, and DC

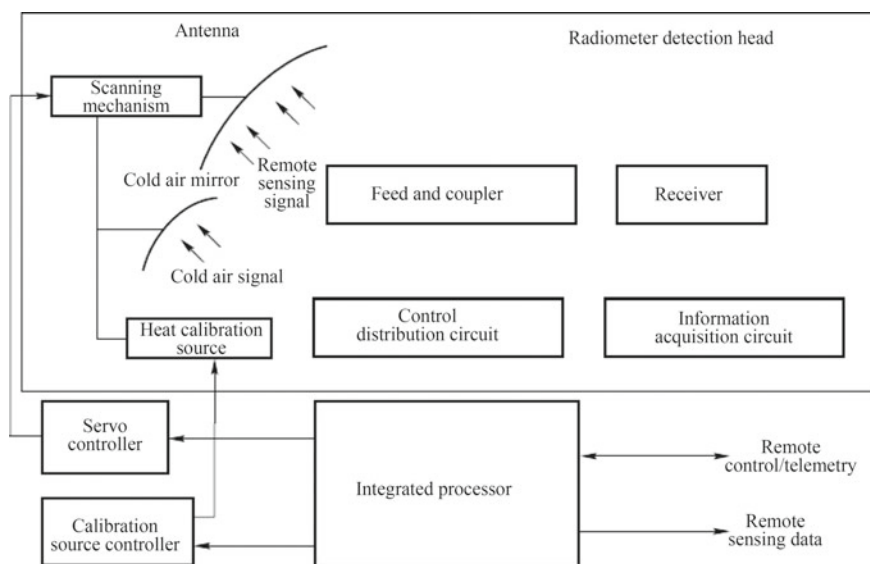


Fig. 8.7 Block diagram of the microwave radiometer

are compensated in the channel, and the exchange of remote sensing data and TT&C is completed.

The integrated processor controls the working state of the microwave radiometer and exchanges information of remote sensing. Its main functions are as follows:

1. According to the results of data processing, the channel gain and channel compensation parameters are automatically adjusted to let the channel work in the optimal state.
2. Receiving angle information sent by the servo controller;
3. Receiving the calibration source body temperature information collected by the heat calibration source controller;
4. The measurement data are formatted and sent to the data management subsystem.
5. Data exchange between indirect instruction and indirect telemetry with data management subsystem

The servo controller drives the detection head of microwave radiometer to perform 360° conical scanning, and feeds back the angle data of antenna rotation to the integrated processor through a synchronous serial bus. The thermal radiation calibration source provides a stable microwave radiation brightness temperature required for calibration and observation. The temperature is collected by the calibration source controller and sent to the integrated processor via the internal serial bus. The locking device locks the detection head during launching, and ensures the rigid connection between the components of the antenna. After the satellite is put into orbit, the restraints between the high-frequency box and the mounting plate is removed by cutting the screw through the pyrotechnic cutter.

8.5.5 Design of Working Mode

Normal working mode

Microwave radiometer is always in the working state during its on-orbit period and transmits remote sensing data to ground station through the data transmission subsystem. With the function of internal calibration, the microwave radiometer corrects the drift of the instrument, and transmits the calibration data to the ground station through the data transmission subsystem. According to the on-orbit state, the microwave radiometer subsystem can be switched between the main and standby by remote control instructions, and the channel parameters and heating mode can be controlled under a certain working mode.

Emergency working mode

When microwave radiometer fails, interfering with other subsystems should be avoided through itself-protection function. If the radiometer antenna is required to stop, the antenna can be slowed down and stopped by shutting down.

8.5.6 *Error Source Analysis and Accuracy Control of Microwave Radiometer Temperature Measurement*

The absolute temperature error comes from three aspects: the error generated by the antenna side lobes, the random error, and the calibration error. The total temperature error is the root mean square of these three errors.

8.5.6.1 Errors Caused by Antenna Side Lobes

The signal received by the antenna of the radiometer is the sum of the signal received by the antenna main lobe and the signal received by the antenna side lobe. The antenna temperature T_A can be expressed as

$$T_A = \eta_M \overline{T_{ML}} + (1 - \eta_M) \overline{T_{SL}}, \quad (8.43)$$

where η_M is the main beam efficiency of the antenna, T_{ML} is the effective apparent temperature contributed by main lobe, and T_{SL} is the effective apparent temperature contributed by the side lobe.

The purpose of radiometric remote sensing is to determine the relationship between the radiometer output voltage V_{OUT} and effective apparent temperature T_{ML} . Estimated based on the antenna pattern, the T_{SL} is approximately 180 K. Since the second term in the above equation is different in the T_{SL} when measuring the heat calibration source and the T_{SL} in other measurement states, the item cannot be eliminated by scaling. The uncertainty of T_{SL} , the source of error, is mainly caused by the uncertainty of sky temperature and Earth temperature, and the fluctuation of satellite temperature.

Based on global experience, the uncertainty of T_{SL} is about +5 K. If η_M is 0.95, the temperature measurement error caused by side lobes is about +0.25 K. The main beam efficiency of the antenna shall be improved to reduce the measurement error caused by side lobes. In addition, the uncertainty of the main beam efficiency of the antenna η_M will also affect the accuracy of temperature measurement. Only when the measurement accuracy of η_M is very high, this error can be eliminated.

8.5.6.2 Random Error

The random error is the temperature measurement sensitivity of the microwave radiometer, which can reach the index of 0.33 K.

8.5.6.3 Calibration Error

The total temperature measurement error of the microwave radiometer is the root mean square of three terms: namely the error caused by antenna side lobe, the random error, and the calibration error. From the previous analysis, it can be seen that the temperature measurement error caused by the antenna side lobe is about 0.25 K and the random error is 0.33 K. The total absolute temperature measurement error is required to be 1 K, so the calibration error value is specified as better than 0.9 K.

Calibration error is defined as the deviation between the brightness temperature of the target and the brightness temperature measured by the radiometer when the radiometer is calibrated. As mentioned above, the calibration error should be better than 0.9 K according to the requirement of 1 K absolute temperature measurement accuracy. Therefore, the END TO END system calibration method should be adopted for radiometer. Based on global experience, the absolute temperature measurement accuracy of the calibration test can reach 1 K by this method.

The uncertainty of thermal calibration source and cold air observation result in the uncertainty of Earth target measurement. Uncertainty in the observation of Earth targets is evaluated as follows:

$$\Delta T_A = \sqrt{\left(\frac{V_A - V_C}{V_H - V_C} \Delta T_H\right)^2 + \left(\frac{V_H - V_A}{V_H - V_C} \Delta T_C\right)^2}, \quad (8.44)$$

Since the uncertainty of the cold space observation is large, the lower the brightness temperature of the measured scene, the larger the measurement error. According to the previous analysis results and the above formula, if $T_A = 180$ K, the error of the calibration measurement is about 0.9 K.

8.5.6.4 Absolute Temperature Measurement Accuracy

The absolute temperature measurement accuracy is the root mean square value of the above three errors. The results show that the absolute temperature measurement accuracy can reach (+0.98 K) and meets the requirements of less than 1 K.

8.6 Design and Analysis of Calibration Radiometer

The main purpose of the calibration radiometer on the satellite is to measure the path delay caused by the signal passing through the atmosphere, and the atmospheric integrated water vapor content and cloud liquid water content, and to provide atmospheric calibration data to the radar altimeter by measuring the liquid water and vapor content in the upper atmosphere.

8.6.1 Principle of Calibration Radiometer

The calibration radiometer transmits atmospheric calibration data to the radar altimeter. The observation route of the calibrated radiometer and their working principle are the same as that of the radar altimeter.

8.6.2 Design and Analysis of Calibration Radiometer

There are two main factors affecting the accuracy of microwave altimeter measurement: tropospheric atmosphere and ionosphere. The influence of the ionosphere can be reduced by using dual-frequency altimeter. The path delay of the altimeter signal can be inverted by using the calibrated radiometer to measure the brightness temperature of atmospheric radiation. The calibration radiometer mainly measures liquid water and water vapor content in the upper atmosphere, and transmits atmospheric calibration data to the radar altimeter. The functions of the calibration radiometer system mainly include: providing atmospheric calibration data to radar altimeter through the measurement of liquid water and vapor content in atmosphere, observing at the same distance with radar altimeter, and using internal calibration mode to correct instrument drift.

The liquid water and water vapor content in the upper atmosphere are measured in frequency bands K and Ka. The atmospheric correction data are provided to radar altimeter to improve the measurement accuracy of radar altimeter.

8.6.3 Calibration Radiometer Configuration and Topological Structure

The connection block diagram of the working principle of the calibration radiometer is shown in Fig. 8.8. The antenna unit includes observation antenna and calibration antenna. An offset parabolic antenna is used as the observation antenna to receive microwave radiation from the atmosphere and the ocean; the calibration antenna consists of three corrugated horn antennas that receive microwave radiation from the cosmic background. The receiving unit includes receivers of the channels K1, K2, and Ka, each of which has a cold backup. The receiver unit is responsible for down-conversion, amplification, filtering, detection, and amplification of the received signal to the level amplitude that is available for acquisition by the digital circuit. The matching load and high-frequency microwave switch that is calibrated for the system are also installed in the receiver unit. The CNC unit is mainly composed of two parts: one is responsible for receiving data acquisition and system control, including

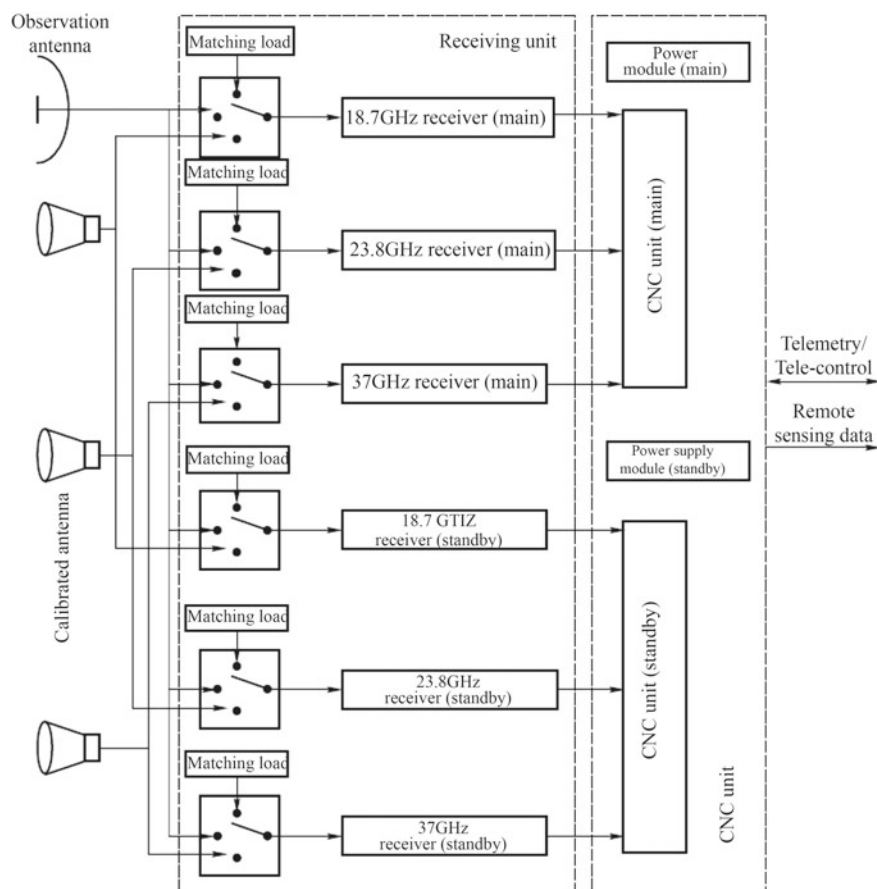


Fig. 8.8 Block diagram of calibration radiometer

system working process control and channel parameter control; the other is responsible for data transmission and communication with satellite system, including downloading scientific data and engineering parameters, receiving satellite ephemeris data, receiving data injection through the bus.

8.6.4 Design of Operating Mode

Normal working mode

During the on-orbit period, the calibration radiometer is always in operating state and transmits the acquired remote sensing data to the ground station through the data transmission subsystem. The drift of the instrument is corrected by the calibration

radiometer with its function of calibration at regular intervals, and the calibration data is transmitted by it to the ground station through the data transmission subsystem.

Emergency mode

When the subsystem fails, the self-protection function should be available to avoid interfering with other subsystems.

8.6.5 Error Source and Accuracy Control of Calibration Radiometer Measurement

Calibration of radiometer measurement error mainly includes equipment system error and calibration error. The system error of the calibration radiometer is determined by the sensitivity and stability of microwave radiometer. Among them, the sensitivity of calibration radiometer is determined by the fluctuation of system noise, which is defined as

$$\Delta T_N = \frac{T_{SYS}}{\sqrt{B\tau}}. \quad (8.45)$$

The stability of calibrated radiometer is affected by the fluctuation of system gain, which is defined as

$$\Delta T_G = T_{SYS} \frac{\Delta G}{G}. \quad (8.46)$$

Since the gain fluctuation and noise fluctuation of the system can be regarded as independent random variables, the system errors caused by them can be defined as

$$\Delta T_{\min} = \sqrt{\Delta T_N^2 + \Delta T_G^2}. \quad (8.47)$$

In the above three formulas, B is the bandwidth; τ is the integration time; ΔG is the system gain fluctuation; T_{SYS} is the system effective noise temperature, which is defined as the sum of the target radiation brightness temperature and the system noise temperature received by the antenna.

Sensitivity can be improved by increasing receiver bandwidth, prolonging integration time and reducing system noise, and system stability can be improved by using high gain stability devices, thereby reducing system error. High gain stability amplifiers are used in the system design, and the system adopts onboard two-point calibration scheme, so the effect of gain fluctuation can be neglected.

Calibration error refers to the uncertainty of the measurement of high-temperature calibration source (matching load) and low-temperature calibration source (cold air background radiation), as well as the error caused by the nonlinearity of the system in the process of brightness temperature inversion. Although the deviations caused

by these error sources are independent and unrelated to each other, their weights are different, and their specific manifestations are related to the characteristics of the system because their effects on calibration errors are not uniform.

8.6.5.1 Calibration Error of Matching Load

The calibration error of matching load mainly includes: emissivity of matching load, reflection between matching load and connecting cable, loss of connecting cable, reflection between connecting cable and switch, loss of switch, leakage of local oscillator, and reverse radiation of receiver.

Thermal radiation of matching load, loss of connecting cable and switch are all related to temperature. The temperature of these key components in the system is measured by the temperature monitor set by the design, and the accuracy of temperature measurement is specified at 0.1 K. The matching load is placed in the receiver, and its temperature is basically the same as the front end of the receiver without significant change. The mismatch of the connection between devices will affect the energy transmission. The reflection coefficient of the connection end must be measured before the system integration. Since the transmittance of the matching load is not equal to 1, the local oscillator leakage and the receiver reverse radiation will enter the receiver through the reflection of the matching load. This effect is also uncertain because it is difficult to accurately obtain the matching load reflectivity and leakage signal. The influence depends on the matching degree of matching load and the size of the leakage signal.

8.6.5.2 Cold Air Background Calibration Error

Cold air background calibration mainly includes loss of cold air calibration antenna, reflection between cold air calibration antenna and connection cable, loss of connection cable, reflection between connection cable and switch, loss of switch, Earth radiation received by the antenna side lobes, cosmic background radiation error, and the effect of satellite structure radiation through the antenna side lobes.

Because the path of the cold air background radiation arriving at the receiver is different from that of the thermal load calibration and the Earth observation, the loss, and reflection of the path should be considered first, and the processing method is the same as that of the thermal load calibration.

In the process of cold air calibration, ground and atmospheric radiation have an impact on the accuracy of cold air calibration through antenna side lobes. With the movement of satellites, this effect may change greatly sometimes. The radiation of satellite structure will also affect the cold air calibration through antenna side lobes. Because the satellite surface is covered with metal materials, the satellite radiation mainly reflects the Earth radiation, which is analyzed according to the satellite layout. Cold air calibration error can be expressed as

$$\Delta Tb_C = \Delta Tb_{SL}, \quad (8.48)$$

where ΔTb_{SL} is the total uncertainty caused by side lobes.

8.6.5.3 System Nonlinear Error

The response function of an ideal corrected radiometer is a linear function, but in practice, the system is not ideally linear. The system nonlinearity as an approximation can be simulated as a square term varying with equipment temperature, which is expressed by maximum nonlinearity uncertainty ΔTb_{NL} .

8.7 Data Processing and Application of Microwave Remote Sensing Satellite

The satellite HY-2 was successfully launched on August 16, 2011. For the first time, the satellite was loaded with active microwave remote sensors (including radar altimeter, microwave scatterometer), passive microwave remote sensors (including microwave scanning radiometer, calibrated microwave radiometer), and precision orbit determination system. The signals detected by the microwave remote sensor are collected, calibrated, processed, and inverted by the ocean satellite ground application system. Many data products such as sea surface height, effective wave height, sea surface wind field, and sea surface temperature, are generated and distributed to users in various fields in the world.

8.7.1 Data Processing

The main payloads of marine dynamic environment satellite are radar altimeter, microwave scatterometer, scanning radiometer, and calibration radiometer. The main task is to monitor and investigate the marine environment, obtain a variety of marine dynamic environmental parameters, including sea surface wind field, wave height, current, sea surface temperature, etc., directly provide measured data for the early warning and prediction of disastrous sea conditions, and support services for marine disaster prevention and mitigation, marine rights and interests protection, marine resources development, marine environmental protection, marine scientific research, and national defense construction.

1. Ocean is the main application target of satellite altimeter. The remote sensing measurement parameter of the satellite altimeter is backscattering coefficient of sea surface, which can be used to inverse sea surface wind speed, effective wave height, and sea surface height by echo waveform.

2. Ocean is also the main application target of satellite scatterometer. The remote sensing measurement parameter of the satellite scatterometer is the backscattering coefficient of the sea surface, which is used to inverse the wind vector of the sea surface.
3. The main application targets of satellite microwave radiometer and calibration radiometer are ocean and atmosphere. Its remote sensing measurement parameter is microwave brightness temperature, which is used to inverse sea surface temperature, wind speed, atmospheric water vapor, etc. The inversed atmospheric water vapor and liquid water provide calibration parameters for altimeter and scatterometer.

The original remote sensing data of the microwave remote sensing satellite is received by the satellite ground station. After preprocessing, such as unpacking, the data processing center is provided with grade 0 data products and other auxiliary products (orbit and attitude files, etc.). The received level 0 data products are made into level 1 data products by the data processing center, and performs product archiving and distribution services. The data processing center is responsible for making level 2 data products on the basis of level 1 products, and then carries out product archiving and distribution services. The general data processing flow is shown in Fig. 8.9.

Payload data processing and product grade are shown in Table 8.7.

8.7.2 *Tsunami Early Warning*

The devastating waves caused by underwater earthquakes, volcanic eruptions or underwater collapses and landslides, which rush into the bay and the seaport, are called tsunami. Tsunami is a very destructive wave, which could bring huge economic losses. Therefore, real-time wave monitoring is an effective means of tsunami warning. The satellite HY-2 has the capability of monitoring sea surface height and effective wave height, and can provide observation data for tsunami monitoring. At 16:38 on April 11, 2012, an earthquake of magnitude 8.5 in the Richter scale occurred in the sea area near the north of Sumatra, Indonesia (2.3° north latitude and 93.1° east longitude), with a focal depth of 20 km. A strong earthquake of magnitude 8.2 occurred again on the same day. The distribution of effective wave heights in the global sea area before and after the Indonesian earthquake was monitored and analyzed by the satellite HY-2.

From the monitoring analysis, it can be determined that the effective wave height of the Indian Ocean, which is most likely to trigger tsunami, does not change much, not exceeding 1 m, before and after the earthquake. Based on the comparison results, it can be preliminarily determined that there will be no tsunami in the Indian Ocean.

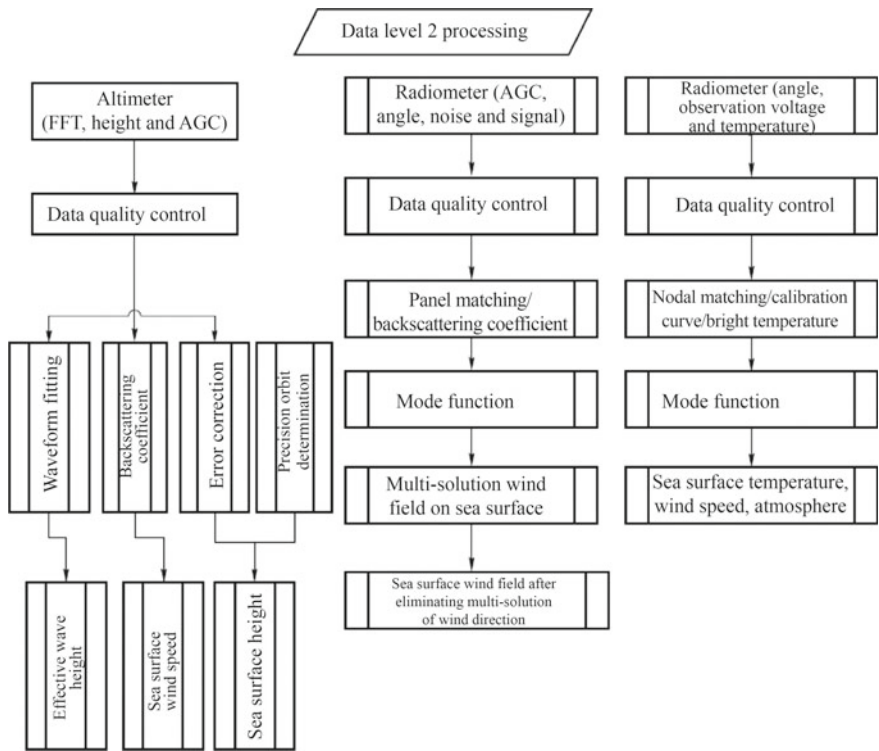


Fig. 8.9 Data processing flow (used in altimeter, scatterometer, radiometer)

8.7.3 Application of Typhoon Monitoring

Typhoon is a tropical cyclone with sustained central wind speed ranging from level 12 to level 13. Typhoon originates from the tropical sea surface, where the temperature is high and a large amount of seawater is evaporated into the air, forming a low-pressure center. As the change of pressure and the motion of the Earth itself, the inflowing air also rotates, forming a counterclockwise rotating air vortex, which is a tropical cyclone. As long as the temperature does not drop, the tropical cyclone will grow larger and larger and eventually form a typhoon. The satellite HY-2 scatterometer observes 90% of the world's sea area every day. Wind field observation has the characteristics of large scale, all-day, all-weather, and global coverage, and can provide real-time typhoon monitoring data in the Northwest Pacific. The sea surface wind field and effective wave height data obtained by the satellite HY-2 can be used to determine the intensity, location, direction, structure and wave intensity of the storm at sea. The results have been applied to the prediction and assessment of storm surges and wave disasters.

Table 8.7 Three data levels for different payloads

	Level 0 data	Level 1 data	Level 2 data
Altimeter	The data products include packet primary header, packet secondary header, and source data. The source data is received by the ground and demodulated and de-formatting	The data products consist of file header and data. Data production includes data format conversion, physical quantity calculation and scanning point location, etc.	The data products include effective wave height, sea-level height, and sub-satellite point sea surface wind speed. Effective wave height is inversed from FFT data, sea surface wind speed is inversed from AGC data and sea surface height is inversed from tracking height data
Scatterometer	The data products are generated by preprocessing of receiving and preprocessing subsystem. They mainly include scientific data products, engineering source package data products, engineering telemetry data products, satellite parameter products, etc.	The data products using satellite receiving preprocessing subsystems obtain data products with positioning information and related description information through preprocessing procedures such as geolocation, land and sea identification, and physical quantity conversion	After data quality control and panel matching, the multi-solution wind field of each wind vector unit is obtained by mode function, and then the unique wind vector solution is obtained by multi-resolution algorithm
Radiometer	The data products include packet primary header, packet secondary header and source data	The data products are composed of file header and data, which are stored according to the parameters at each pixel point, and transformed by physical quantity and geographic location	Multiple panels of each pixel of the data have been matched to their spatial positions. It consists of the same brightness temperature in different ground footprints corresponding to different frequencies. The relationship between the brightness temperature measured by radiometer and sea surface parameters is established, and then the inversion algorithm is formed

8.7.4 Application in Fishery Environment and Fishery Information Service

The satellite HY-2 can provide global fishing environment information such as sea surface temperature, sea surface wind field, effective wave height, sea surface height, ocean current, mesoscale eddy, and also global key fishing environment and fishing situation information for ocean fishing. The satellite HY-2 combines with foreign marine satellite data acquired by the “Real-time Automatic Acquisition System of Marine Remote Sensing Information,” and carries out weekly fishery environmental analysis, fishery analysis and forecasting for Pacific Tuna, North Pacific squid, South East Pacific squid, Southwest Atlantic salmon, Mid-Atlantic tuna, and seven sea areas. By means of the satellite Beidou and broadcasting satellite, it provides services such as fishing forecast, sea condition analysis, and quasi-real-time return of field operation data to marine fishery enterprises, which greatly improves the overall technical level of satellite remote sensing application in China’s ocean fishing grounds.

8.7.5 Sea-Level Change Monitoring

With the rapid expansion of the impact of human activities on the marine and atmospheric systems, global warming and sea-level rise have become major global environmental problems. Sea-level rise poses a great threat to human living environment and has caused great attention of scientists and governments all over the world. Satellite radar altimeter has unique advantages in global sea-level change monitoring. The acquired sea-level data has become an important data source in the study of global mean sea-level rise.

China National Satellite Ocean Application Center has produced monthly average and annual average of China’s offshore and adjacent sea areas, as well as sea-level data products that changed from the previous year based on the combined remote sensing data of the satellite HY-2 altimeter. The marine forecasting, disaster prevention, and mitigation departments can effectively carry out the corresponding sea-level change prediction and the development of marine environmental products by using these sea-level change products, and provide information services to the public and relevant marine management and production departments.

8.8 Conclusion

Marine microwave remote sensing satellites usually carry microwave payloads, such as microwave radiometer, microwave scatterometer, radar altimeter, and synthetic

aperture radar. They are mainly used to obtain ocean dynamic environmental parameters, such as sea surface wind field, sea surface height field, wave field, ocean gravity field, ocean circulation, sea ice, effective wave height, and sea surface temperature field. Two important indicators to measure the capability of ocean dynamic environment satellite observation and application include the observation accuracy and spatial and temporal resolution of satellite. The observation accuracy and spatial-temporal resolution of the satellite will be greatly improved with the continuous progress of ocean data processing technology and microwave remote sensing technology.

Reference

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Chapter 9

Design and Analysis of Optical Remote Sensing Satellite System on Geostationary Orbit



9.1 Overview

Geostationary Orbit Optical Remote Sensing System (hereinafter referred to as “GEO Optical Remote Sensing System”) combines high spatial resolution and extremely high temporal resolution, which is an important direction for the development of ground remote sensing system. High-resolution optical remote sensing system in geosynchronous orbit can quickly acquire the information on interested objects through its real-time task response ability. Unlike previous GEO meteorological satellites or missile early warning satellites, the satellite with the high-resolution optical remote sensing system is generally with the spatial resolution of visible light load on geosynchronous orbit superior to hundreds of meters order of magnitude, and infrared load resolution superior to kilometers order of magnitude.

Through rapid pointing adjustment, area array imaging, and efficient multi-stitch imaging, the GEO optical remote sensing system can achieve a rapid response and high-frequency continuous detection on disaster events with different impact ranges, thus satisfying the needs of emergency observation tasks for various disasters such as earthquakes, debris flows, forest fires, floods, snow disasters, and volcanic eruptions, and playing a major role in the field of people’s livelihood.

Combining with China’s first geostationary orbit high-resolution optical remote sensing satellite GF-4, this chapter focuses on the overall design and application of GEO optical remote sensing satellite systems, including overall design elements, on-orbit imaging pattern design, area array imaging quality analysis, on-orbit calibration, and image processing techniques.

9.1.1 Development Overview

It is supposed that the US satellites KH-12 and Hubble with the primary mirror aperture of 2.4–3 m have the technical ability to achieve resolution better than 10 m

on geostationary orbit. However, due to the large number of LEO optical satellites that can be used for military reconnaissance in the United States, and all means of reconnaissance except space-based reconnaissance are also available; the demand for geostationary orbit below 10 m resolution is not strong.

In 2009, Europe Herschel Space Telescope (Herschel) with an aperture of 3.5 m is launched, and GEO optical remote sensing system and GEO optical remote sensing satellite platform with high attitude control accuracy and high maneuver ability are actively developed based on its technology. Astrium, a strong European company in the field of GEO optical remote sensing technology, carried out a series of satellite design and demonstration, such as Geo-Africa, Geo-Oculus, and HRGeo.

China launched its first geostationary orbit high-resolution optical remote sensing satellite GF-4 on December 29, 2015. GF-4 uses GEO remote sensing satellite platform to carry visible light and medium-wave infrared common-aperture high-resolution imager with sub-satellite point's spatial resolution of visible light panchromatic/multispectral of 50 m, the resolution of the sub-satellite point of the mid-wave infrared spectrum of 400 m, and the swath of each spectrum greater than 400×400 km. Taking the advantages of long-term residence over a fixed area and fast pointing adjustment, GF-4 realized the combination of high temporal resolution and high spatial resolution with quick response to the observation missions of China and its surrounding areas.

9.1.2 Development Trend

In the future, the trend of GEO optical remote sensing is as follows:

1. GEO optical remote sensing has created a new model for remote sensing applications: due to its special satellite–Earth relationship and imaging system, GEO optical remote sensing system can not only quickly and frequently detect high-frequency targets, but also has fast mission response capability, high-frequency repeated detection capability and wide-range multi-target continuous monitoring capability.
2. The application efficiency of remote sensing system can be improved through the collaborative work of high- and low-orbit remote sensing system, in which GEO optical remote sensing system is capable of real-time interactive control between satellite and Earth. Compared with the satellite networking mode, the construction of a coordinated integrated observation system for high- and low-orbit satellites can significantly improve the efficiency of space-based resources application by taking the advantages of continuous observed high temporal resolution.
3. The spatial resolution and spectral resolution are continuously improved, and the application range is further expanded. With the rapid development of optical remote sensing technology, its spatial resolution and spectral resolution will be further improved, and its application range will be further expanded.

9.2 Demand Analysis and Technical Characteristics

9.2.1 *Demand Analysis*

GEO optical remote sensing system is ideal for missions with high timeliness and continuity requirements such as Earth environment science, national security, disaster early warning, and emergency response.

In the field of application of the geo-environmental science, the Sun-synchronous orbit optical remote sensing system has a relatively long revisit period, so it is impossible to monitor environmental events in a relatively short time interval, which is difficult to meet the needs of daily change monitoring. GEO optical satellite can achieve hourly continuous monitoring and observation, and the repeated observation frequency can be up to the second level, which can meet the requirements of observation frequency for short-period environmental phenomena and real-time monitoring of emergencies, realize real-time observation of key areas, and greatly enhance the ability of environmental monitoring, so as to meet the needs of observational data for terrestrial, marine, atmospheric environmental monitoring, etc.

In the field of national security applications, the system to be designed should quickly monitor target feature data under the emphasis on timeliness and high frequency for observing and monitoring of specific targets, which is of great significance for grasping the direction, speed of travel, and intention of action. With the ability of GEO remote sensing satellite on fixed-point gaze and near-real-time mission response, continuous monitoring of key areas and continuous tracking of key targets can be achieved through mutual guidance and cooperation with low-orbit satellites, so that the system effectiveness of space-based resources can be fully utilized to achieve the combination of high spatial resolution and high temporal resolution.

In the field of disaster early warning and emergency response, disasters are often characterized by sudden occurrence, rapid development, and serious impact. In response to most of the disasters and environmental pollution emergencies, it is very important to obtain the disaster monitoring data as soon as possible. In the process of disaster relief, continuous acquisition of disaster change detection data with high frequency will help decision-making at all levels and the smooth development of emergency relief work, thereby minimizing the losses caused by disasters to the national economy.

9.2.2 *Technical Characteristics of GEO Optical Remote Sensing Satellite*

The special satellite–Earth relationship and the area array imaging system endow the GEO optical remote sensing system with various technical characteristics, which are summarized as follows:

1. It is easy to realize high-frequency repetitive observation ability, acquire short-period change data, and realize fast “maneuvering-staring” mode by using area array imaging system.
2. The optical system and focal plane are shared in each detection band by time-sharing imaging method, and the spectral band is switched by rotating the filter wheel.
3. The exposure time can be dynamically adjusted according to the observation time, the observation position, the observation target, or even the atmospheric environment to obtain high-quality image data.
4. Exposure time is tens of times as long as that of the LEO satellite. In the imaging process, the higher attitude measurement, control, and stabilization accuracy of the satellite are required.

9.3 Analysis of Coverage Characteristics and Time Resolution of GEO Optical Remote Sensing System

9.3.1 Orbit Selection Analysis

Geostationary orbit satellites are relatively geostationary and suitable for area array staring mode. Its observation effect in the middle and low latitudes is better than that in the high latitudes. The observation effect in the longitude direction near the fixed position longitude is better than that in the East–West direction.

Comparing with geostationary orbit, inclined geosynchronous orbit can obtain the positive 8-shaped, inclined 8-shaped or water droplet-shaped sub-satellite point trajectory through proper inclination and eccentricity design. The large latitude and longitude range of the sub-satellite point trajectory in inclined geosynchronous orbit can improve the observation effect in the high latitude area when the satellite moves over the high latitude area. However, in order to achieve gaze imaging, the accurate orientation of the optical axis of the camera shall be ensured by the attitude control system.

9.3.2 Geometric Analysis of Earth Observation

9.3.2.1 Angle Analysis of Satellite Attitude by Imaging

Since the sub-satellite point is a fixed point, the attitude angle of the satellite is fixed when the GEO optical satellite observes the specific geographical location area. When imaging a target area, the camera’s optical axis is pointed to the target area by the whole satellite attitude maneuver, according to which the roll angle and pitch angle of the satellite attitude are determined. Considering the difficulty of satellite control, an attitude pointing mode with a fixed zero yaw angle is usually adopted.

Table 9.1 Pitch angle (east–west direction) as a function of latitude and longitude (°)

	60°E	80°E	100°E	120°E	140°E	160°E	180°E
60°N	−3.89	−2.95	−1.59	0.00	1.59	2.95	3.89
40°N	−6.07	−4.67	−2.54	0.00	2.54	4.67	6.07
20°N	−7.54	−5.85	−3.21	0.00	3.21	5.85	7.54
0°N	−8.06	−6.27	−3.45	0.00	3.45	6.27	8.06

Table 9.2 Roll angle (north–south direction) as a function of latitude and longitude (°)

	60°E	80°E	100°E	120°E	140°E	160°E	180°E
60°N	7.73	7.90	8.01	8.06	8.01	7.90	7.73
40°N	5.85	6.06	6.21	6.27	6.21	6.06	5.85
20°N	3.16	3.30	3.41	3.45	3.41	3.30	3.16
0°N	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 9.3 Yaw angle (the angle between the +Z axis of the satellite and the +Z axis of the orbital system) as a function of latitude and longitude (°)

	60°E	80°E	100°E	120°E	140°E	160°E	180°E
60°N	8.65	8.43	8.17	8.06	8.17	8.43	8.65
40°N	8.43	7.65	6.71	6.27	6.71	7.65	8.43
20°N	8.17	6.71	4.68	3.45	4.68	6.71	8.17
0°N	8.06	6.27	3.45	0.00	3.45	6.27	8.06

Assuming that a GEO optical remote sensing satellite is positioned at (0°N,120°E), the pitch, roll, and yaw angles of the satellite are listed in Tables 9.1, 9.2, 9.3, respectively, in order to make the optical axis of the camera point at different latitudes and longitudes.

9.3.2.2 Analysis of Satellite Angle for to-Earth Observation

The observation angle of the GEO optical satellite can be characterized by the azimuth angle and the altitude angle of the satellite when observing the target area.

The azimuth angle and altitude angle of the GEO optical satellite are only related to the longitude and latitude of the target area. Taking the geostationary orbit optical satellite positioning at (0°N,120°E) as an example, the altitude angle and azimuth angle of the satellite imaging at different longitude and latitude positions are shown in Tables 9.4 and 9.5.

Table 9.4 Satellite altitude angle for imaging at different latitudes and longitudes (°)

Latitude	Longitude						
	60°E	80°E	100°E	120°E	140°E	160°E	180°E
60°N	5.83	14.09	19.85	21.94	19.85	14.09	5.83
40°N	14.09	28.29	39.33	43.73	39.33	28.29	14.09
20°N	19.85	39.33	57.33	66.55	57.33	39.33	19.85
0°	21.94	43.73	66.55	90.00	66.55	43.73	21.94

Table 9.5 Satellite azimuth angle for imaging at different latitudes and longitudes (°)

Latitude	Longitude						
	60°E	80°E	100°E	120°E	140°E	160°E	180°E
60°N	117	136	157	180	203	224	243
40°N	110	127	150	180	210	233	250
20°N	101	112	133	180	227	248	259
0°	90	90	90	0	270	270	270

9.3.3 Time Resolution Analysis

9.3.3.1 Observation Characteristics of High-Time Efficiency of GEO Optical Remote Sensing Satellite

The high temporal resolution and timeliness of GEO optical satellites are mainly reflected in the following two aspects:

- (1) When the meteorological conditions on the ground are unfavorable, the satellite can use the cloud gap to capture the opportunity of Earth observation, so as to improve the observation effect of the target area.
- (2) The GEO optical satellite with high-time resolution makes use of the advantage of relative ground stationary to observe the target area repeatedly in a period of time to acquire the dynamic change process data of the target area.

Because the moving targets (clouds and typhoons) have the characteristics of continuous movement, they will change their geographic position at a certain speed. Through high-frequency gaze imaging in the same region, the relative background positional change of the target can be observed on the images of different time intervals. Combined with the satellite image parameters such as satellite imaging time and imaging orientation, the motion direction, and motion speed of the moving target can be calculated, so that the type and the mode of the moving target can be judged and evaluated.

9.3.3.2 Imaging Response Speed and Imaging Interval Analysis

The imaging response speed refers to the time interval from the time when the user issues an imaging command to the time that the image of the target area is received by the ground application center. The minute-level imaging response speed can be achieved by the GEO optical satellite. The imaging interval generally refers to the interval time between two imaging. It is an index reflecting the repetitive observation ability of a remote sensing system. The period of acquiring a group of images by GEO optical satellite can reach the second level or even higher.

9.3.3.3 Analysis of Regional Splicing and Inspections Ability

The time required for the high-altitude optical satellite to complete a splicing in a designated region is related to factors such as the size, geometry, and geographic location of the target area.

Taking the observation of China's territory as an example, the satellite attitude maneuver angle will not exceed 10° when switching between any three single-view areas. This process time is mainly divided into three parts: satellite attitude maneuver time, camera imaging time, and data transmission time. According to the current attitude maneuver, imaging, and digital transmission, the time for completing inspections in any three areas within China national territory shall not exceed 10 min.

9.4 Key Performance Indicators for Imaging Quality of GEO Optical Remote Sensing Satellite

GEO optical satellite can be loaded with a visible light remote sensing system, infrared remote sensing system, and hyperspectral remote sensing system. The imaging quality of the satellite includes two parts: radiation quality and geometric quality. The evaluation indicators of radiation quality mainly include MTF, SNR, and dynamic range. The evaluation indicators of geometric quality mainly include geometric positioning accuracy, geometric distortion of image, and spectral registration accuracy. For the detailed indicators, refer to the key performance indicators of imaging quality of visible light remote sensing system, infrared remote sensing system, and hyperspectral remote sensing system.

9.5 Design and Analysis of Imaging Quality of GEO Optical Remote Sensing Satellite System

The imaging quality of the GEO optical satellite may directly affect the quality of data acquired by users. The key design elements of imaging quality include selection of imaging system, design of optical system, selection and configuration of spectral bands, selection of detectors, imaging width, resolution of ground pixels, exposure time planning, etc.

9.5.1 Selection of Imaging System

For GEO optical satellite design, the area array gaze imaging system should be mainly considered. Firstly, the past push-broom type imaging system with low orbit linear array images by utilizing the relative ground push-broom motion of satellites, while the linear array push-broom imaging system should not be used in the geostationary orbit satellite because of stable satellite–Earth relationship and no relative motion. With a very flexible and targeted configuration for the observation area, the area array gaze imaging system can effectively grasp the good imaging opportunity with a very-high-time resolution. Secondly, under the help of area array imaging system, the advantages of geostationary orbit satellites relative to fixed objects will be brought into full play to flexibly adjust the exposure time of gaze imaging, and to significantly improve the signal-to-noise ratio of images under complex imaging conditions.

9.5.2 Selection of Optical System Forms

Optical satellites with multiple imaging channels (such as visible light, medium-wave infrared, longwave infrared, etc.) are usually designed with common-aperture optical system design and share a front-end optical system that separates the channels by splitting. The optical system is independently set at back-end, and the filter box or filter wheel can be used to subdivide the spectrum in the channel.

In order to achieve high resolution, reflective type is widely used for the common-aperture front optical system to meet the demand on the large aperture, long focal length, and high image quality. Typical optical system configurations are shown in Fig. 9.1.

Total reflection achromatic optical system can meet the requirements of large aperture and long focal length that the refraction system cannot reach. Since the optical system has an optical path folding, the system can be greatly reduced in size and weight. This is particularly beneficial for space applications and meets the mission requirements of GEO optical remote sensing satellites.

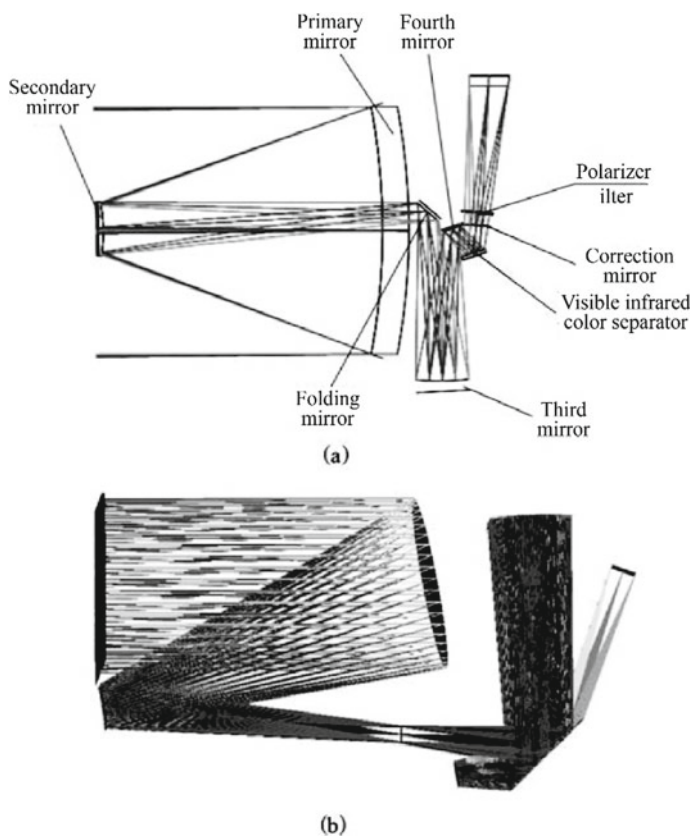


Fig. 9.1 High resolution optical system configuration. **a** Coaxial third-mirror optical system. **b** Off-axis third-mirror optical system

9.5.3 Band Selection and Configuration

The corresponding spectral ranges should be configured according to the application requirements. GEO optical satellites can usually be configured with full chromatographic bands, multispectral spectral bands, and infrared spectral bands.

9.5.3.1 Analysis of Full Chromatographic Band Configuration

For the task of conventional land observation, full chromatographic band can make full use of the spectral response of the detector to obtain clear images of key observation areas and targets.

9.5.3.2 Analysis of Multispectral Band Configuration

With the configuration of multispectral bands, the spectral and color characteristics of the target surface can be reflected. The fusion of multispectral and panchromatic images can enrich the information, which is more conducive to visual interpretation, the effect improvement of remote sensing detection, and better serving remote sensing applications. Therefore, on the basis of high-resolution panchromatic images, adding multispectral detection capability can provide powerful information support for land and resources survey, environmental protection, mineral resources exploration, and other fields.

9.5.3.3 Analysis of Medium/Longwave Infrared Spectrum Segment Configuration

In summary, the infrared (medium/long wave) spectral range can compensate for the inability to image in the visible spectrum at night, and achieve full-day imaging. The mid-wave infrared spectrum has a unique advantage for high-temperature targets or targets with large temperature differences to the background.

9.5.4 Selection of Detectors

For GEO optical satellites, area array detector is generally used to obtain target image information. According to the current development of detector, different types of detectors must be used to obtain the information in different spectral bands from visible light to infrared light.

9.5.4.1 Selection of Visible Channel Detectors

At present, the widely used visible light area array detectors are CCD and CMOS. However, there are fundamental differences in the structure and readout between CCD and CMOS detector.

From the perspective of detector technology development, after decades of sustained development, CCD detectors are matured in technology and manufacturing processes, and their performance indicators have been gradually improved. At present, it has been widely used in the fields of scientific exploration and satellite remote sensing. Since the twenty-first century, with the improvement of CMOS detector technology, its imaging performance has been greatly improved. Because the CMOS detector has the advantages of high integration and simple imaging circuit, its technology development and application have achieved rapid development.

CMOS detector with unique advantages in electronic shutter, frame transfer speed, readout noise, and anti-dispersion is more suitable for GEO remote sensing applications. At present, the CMOS detector has the engineering development conditions of large-scale visible plane array focal plane module, which can meet the application requirements of GEO optical satellite's wide imaging observation.

9.5.4.2 Selection of Infrared Channel Detectors

Mercury cadmium telluride (HgCdTe) detector is widely used in infrared spectrum at present. Because of the refrigeration requirement, the detector is mostly integrated with the refrigerator, as shown in Fig. 9.2. The HgCdTe infrared detector has the inherent properties of bad pixels, and because the indium column is connected with the readout circuit made of Si and the HgCdTe separately, the device will be impacted by thermal stress when it undergoes many cold and thermal cycles, which will easily lead to the disconnection or fracture of the connecting structure, causing the photosensitive charge to be unreadable or the number of bad pixels increases. Therefore, long life, high reliability refrigerator technology, and further improvement of this type of array detector technology are the key technologies to achieve long life and high reliability infrared spectral imaging detector. Figure 9.2 shows an infrared detector and a refrigeration unit.

9.5.5 Design of Single-Scene Imaging Swath

For the GEO optical satellite with the area array imaging system, the ground area corresponding to the effective FOV of the satellite's Earth observation is defined as a single-scene coverage area. If the effective FOV is $0.8^\circ \times 0.8^\circ$, the corresponding sub-satellite point has a single-scene width of 500×500 km. When imaging on-orbit, the curvature of the Earth also has a certain effect on the single-scene width. The single-scene swath shows an upward trend with the increase of longitude and latitude (relative to the sub-satellite point). In addition, the curvature of the Earth

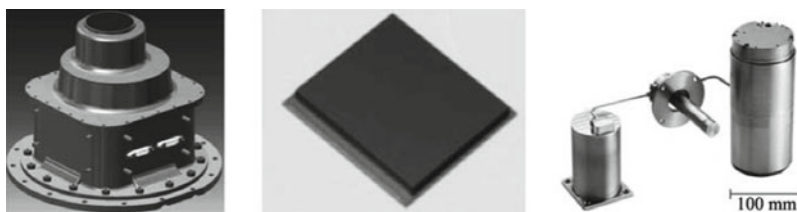


Fig. 9.2 Infrared detector and refrigerator assembly

also affects the geometric distortion in the single-scene swath. Geometric distortion within a frame can be eliminated by ground image processing.

9.5.6 Design of Ground Pixel Resolution

Calculation formula for the ground pixel resolution is as follows:

$$\text{GSD} = d/f \times H,$$
(9.1)

where H is the distance from the camera to the ground scene, which is taken as 35,786 km for the sub-satellite point, d is the pixel size, f is the focal length of the camera optical system, and GSD is the resolution of the ground pixel. According to the analysis of the detector and optical system, the ground pixel resolution of a satellite's sub-satellite point is calculated as shown in Table 9.6.

The effect of the Earth curvature on the resolution of the ground pixels should also be considered in the actual imaging. With the increase of longitude and latitude (relative to sub-satellite point), the resolution of ground pixels decreases. The resolution of sub-satellite point is the highest, and the closer to the edge of FOV, the faster the resolution decreases.

As can be seen from Fig. 9.3, the area on the sphere entering a single pixel of the camera is larger than the sub-satellite point, and its area varies with the latitude and longitude of the target. The change rule is that the farther away from the sub-satellite point, the larger the area. This causes the camera resolution to drop. The ground area corresponding to a pixel includes two dimensions: east and west, south and north. The equivalent ground pixel resolution of a pixel is defined as

$$\text{GSD}_{\text{eff}} = \sqrt{\delta A},$$
(9.2)

where GSD_{eff} is equivalent ground pixel resolution, and δA is the ground area corresponding to a pixel. Tables 9.7 and 9.8 show the ground pixel resolution for satellite imaging at different latitudes and longitudes.

Table 9.6 Resolution of sub-satellite point ground pixel

Channel		Pixel size/ μm	Distance/km	Focal length/mm	Sub-satellite point GSD/m
VNIR	CMOS	9×9	35,786	6600	48.8×48.8
MWIR	Mercury cadmium telluride scheme	15×15	35,786	1350	397.4×397.4

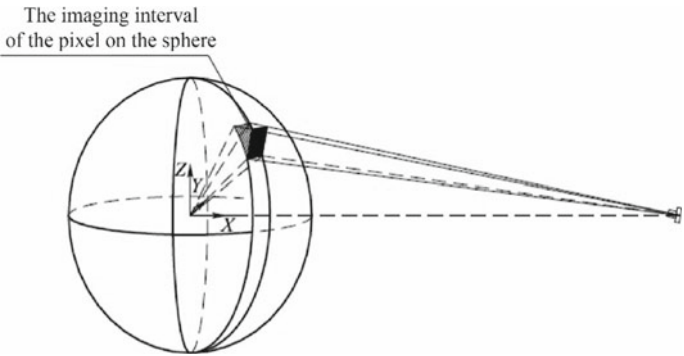


Fig. 9.3 Effect of Earth curvature on resolution

Table 9.7 Equivalent GSD (VNIR Channel) for satellite imaging at different longitudes and latitudes, in m

Latitude	Longitude						
	50°E	70°E	90°E	110°E	130°E	150°E	170°E
60°N	–	110.43	92.13	87.38	92.13	110.43	–
40°N	110.67	76.57	64.61	61.33	64.61	76.57	110.67
20°N	92.53	64.75	54.44	51.56	54.44	64.75	92.53
0°	87.80	61.50	51.58	48.80	51.58	61.50	87.80

Table 9.8 Equivalent GSD (MWIR Channel) for satellite imaging at different longitudes and latitudes, in m

Latitude	Longitude						
	50°E	70°E	90°E	110°E	130°E	150°E	170°E
60°N	–	900	751	712	751	900	–
40°N	902	624	526	500	526	624	902
20°N	754	528	444	420	444	528	754
0°	715	501	420	398	420	501	715

9.5.7 Exposure Time Planning

GEO optical satellite has a large span of visible geographic area. When visiting different regions at different times and locations, the illumination conditions may vary greatly. This is mainly reflected in the following two aspects:

- (a) At some time of the day, different geographical locations have different lighting conditions.
- (b) The illumination condition of the same geographic location will change greatly at different times.

Table 9.9 Radiation matrix of entry pupil of full chromatographic band, in W/(sr cm²)

Band	0.45–0.90 μm						
	0.05	0.1	0.2	0.4	0.6	0.8	1
80	11.50	26.91	44.14	78.97	114.30	150.12	186.44
60	10.48	23.66	38.42	68.31	98.71	129.61	161.04
40	9.14	18.14	28.26	48.87	69.98	91.60	113.76
20	7.30	10.90	14.98	23.40	32.17	41.34	50.93
10	4.95	6.08	7.37	10.02	12.82	15.79	18.98

When imaging by the visible light channel of the camera, the spectral reflectance of the ground target cannot be estimated, and the imaging with large area contains various information of the ground objects, in which the range of the ground reflectance is relatively wide. In order to take into account most of the information of the ground objects, the exposure time is set based on the sun’s altitude angle.

The radiance of the entrance pupil of the sub-satellite point camera is simulated by the software 6S radiation atmosphere transmission under the conditions of the sun altitude angle of 10°–80° and the ground object reflectivity of 0.05–1, and its result is used as the exposure time analysis input. Take the whole chromatographic band as an example, the radiance matrix is shown in Table 9.9.

Combined with the laboratory radiation calibration test, the dynamic range of the test can be ensured to cover the radiance range. Finally, the appropriate exposure time is determined according to the test results. An exposure time is set every 10° solar altitude angle for imaging, by which the dynamic high-end (0.8 reflectance) image is unsaturated and meets the requirement of signal-to-noise ratio. For the high-resolution imager of China’s on-orbit satellite GF-4, the parameters of the high-resolution imager are suggested in Table 9.10 for different solar altitude angles (for reference only).

For surface water targets, the impact of mirror reflection on imaging in some cases shall be considered because the water body has mirror reflection characteristics. For cloud targets, the reflectivity is generally up to 90%. Since the reflection angle range of clouds is large, the reflection light of clouds has a great influence on satellite imaging.

Table 9.10 Visible light channel parameter setting table of high-resolution imager

Solar altitude angle/(°)	Exposure time/ms				
	B1	B2	B3	B4	B5
80–40	2	10	8	12	12
40–20	4	12	20	16	20
10–0	20	50	50	50	50

9.6 On-Orbit Imaging Mode Design

The GEO optical satellite is characterized by its great flexibility in working mode, fast response, and real-time gaze. According to the characteristics of GEO optical satellites and their application requirements, the working mode is set as follows.

9.6.1 Real-Time Video Gaze Mode

In the real-time video gaze imaging mode, the satellite directs the camera optical axis to the target area and keep it still by the satellite attitude maneuver, and a series of time-series images is acquired in a certain time interval to form a video, which is sent to the ground station in near real time by the data transmission system. This mode is suitable for analysis of the moving targets and changing phenomena to obtain the change information and law of the changes in the target and phenomena.

9.6.2 Regional Observation Model

In the regional observation mode, the user can customize an imaging area, including the area position, shape, and area size. The number and the angle of the satellite attitude step maneuver can be determined based on the optimal path planning on the ground or on the satellite itself. The satellite performs a small-angle attitude stepping maneuver to adjust the camera's pointing direction according to the instructions, and continuously stitches the imaging strips into an image covering the specified imaging area, and at the same time transmit the image data to the ground station.

9.6.3 Maneuver Inspection Mode

In the maneuver inspection mode, the satellite attitude maneuvering process can be developed on the ground station or on the satellite according to the optimal path plan for multiple regions of interest within the satellite imaging area selected by user, including the location, shape, and area of each region. The satellite completes continuous imaging of multiple regions of interest by attitude maneuvering in accordance with the instruction. Each region can be either a single-scene area or a multi-view stitching area.

9.7 Scheme Description of High-Resolution GEO Imager

The high-resolution imager of China's satellite GF-4 has the imaging capability in visible light and medium-wave infrared spectrum segments with visible panchromatic/multispectral spatial resolution of 50 m (sub-satellite point) and the medium-wave infrared spectrum segment spatial resolution of 400 m (sub-satellite point).

9.7.1 Camera Function Definition

The main task of the high-resolution imager of GF-4 is to complete the imaging of the mission target with the cooperation of the whole satellite attitude maneuver. The main functions are as follows:

- (1) According to the task information injected by the ground station, the visible light and infrared imaging are performed after the whole satellite attitude maneuvers to the designated region of interest, thus obtaining the panchromatic, multispectral, and infrared image data of the target.
- (2) The exposure time of satellite imaging should be matched with the solar altitude angle of observation to obtain optimal imaging quality. Therefore, a high-resolution imager should have the function of adjusting exposure time on-orbit.
- (3) The satellite adopts a time-sharing imaging mode, and the imaging spectral band should be selected according to the mission requirements. Therefore, the high-resolution imager should have a filter switching function.
- (4) For infrared channel imaging, the focal plane should work at a low temperature, so the infrared channel should have infrared focal plane refrigeration function, and the refrigeration capacity should meet the working requirements of infrared focal plane detector.
- (5) For infrared channel imaging, radiation nonuniformity should be corrected by high-resolution imager, so infrared channel should have onboard calibration function.

9.7.2 System Task Constraints

9.7.2.1 Task-Level Constraints

The satellite operates in a geostationary geosynchronous orbit of 35,786 km, whose observing area covers China's territory and surrounding areas. According to the ground mission planning, the surface scene at the target position should be imaged by satellite with the visible spectrum range from 0.45 to 0.90 μm , the resolution

at the sub-satellite point of 50 m and the single-scene swath of 400×400 km, or with the mid-wave infrared spectrum range from 3.5 to 4.1 μm , the resolution at the sub-satellite point of 400 m and the single-scene swath of 400×400 km.

9.7.2.2 Design Constraints for Large-Scale Engineering Systems

In order to ensure the accuracy of data inversion and the effect of quantitative application, it is required that the high-end signal-to-noise ratio of visible light spectral band is better than 46 dB (solar altitude angle 80° , surface reflectance 0.8), the low-end signal-to-noise ratio is better than 23 dB (solar altitude angle 10° , surface reflectance 0.05), the temperature measurement range of infrared spectral band is 240–650 K, and NETD is better than 0.2 K (300 K blackbody). The auxiliary data and image data are processed together and sent to the ground application system.

9.7.2.3 Constraints on Satellite Overall Design

In order to ensure satellite performance on-orbit, reliability and interface matching between subsystems, design requirements will be put forward on high-resolution imager from the perspective of the satellite system.

In order to ensure the on-orbit dynamic imaging quality, it is required that the out-of-band integral response of each band of the high-resolution imager should be less than 5%, the accuracy of the band range should be less than 15 nm, and the static MTF should be better than 0.10–0.15; the absolute laboratory radiometric calibration accuracy of the visible light channel should be better than 7%, the relative accuracy better than 3%; and the absolute laboratory radiometric calibration accuracy of the infrared channel should be better than 2 K (at 300 K), relative accuracy better than 3% (at 300 K); quantization bit of visible channel and infrared channel is 10 bit and 12 bit, respectively.

In order to match the interface between high-resolution imager and other on-satellite subsystems, it is required that the mass of high-resolution imager is not more than 660 kg, the peak power consumption is less than 1000 W, and the design life is 8 years.

9.7.3 System Configuration and Topology

The high-resolution imager subsystem is mainly composed of camera body, lens hood, visible light controller, infrared controller, infrared refrigeration controller, camera thermometer, etc. The system composition is shown in Fig. 9.4.

The main body of the camera obtains the spectral signal of the ground scenes, which converts the spectral signal into an electrical signal and sends it to the data transmission system. The spectrum switching function, on-orbit focusing function,

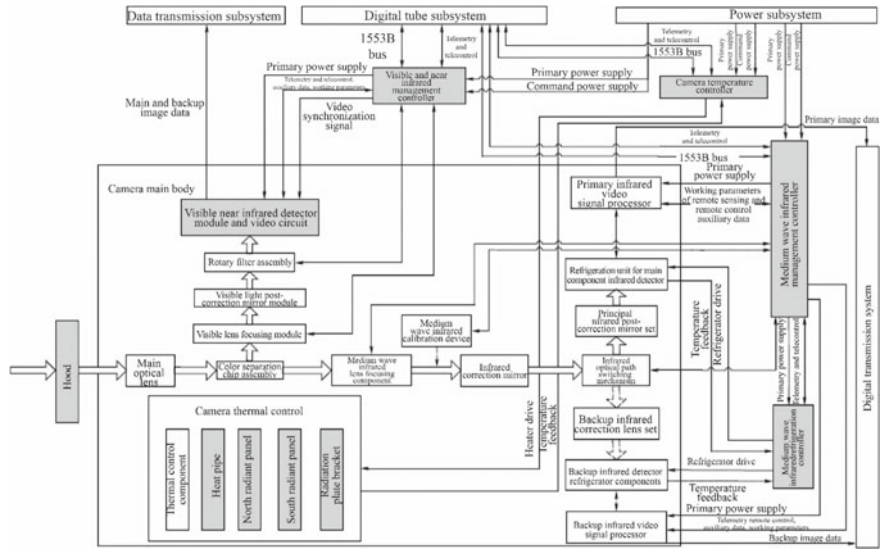


Fig. 9.4 Composition of high-resolution imager for GEO

infrared onboard calibration function, infrared detector refrigeration function, and the switching between the main and standby infrared channels can be achieved by rotary filter module, focusing mechanism, calibration device, pulse tube cooler and, infrared light path switching mechanism, respectively.

9.7.4 Design of Camera Working Mode

9.7.4.1 Visible Light Channel Working Mode Design

The working modes of the visible light channel are described as follows:

In a **single-band single imaging mode**, an image is formed by the high-resolution imager according to the imaging instruction after the imaging band is selected according to the instructions and the filter is switched in place, and then high-resolution imager enters the waiting imaging mode.

In a **full-band single imaging mode**, the designated area is imaged once in each of the five spectral ranges, and then the high-resolution imager enters the waiting imaging mode.

In a **single-band continuous imaging mode**, continuous imaging is performed in a fixed imaging period in the same spectral band until the next instruction is received.

In a **full-band continuous imaging mode**, continuous imaging is performed in five different spectral bands in a fixed imaging period until the next instruction is received.

In a **focusing mode**, the focal plane position is adjusted according to the focusing power-up instruction and focusing parameters setting instruction.

In a **wait for imaging mode**, the visible light channel controller and video circuit are powered-up in the state of waiting for the instruction.

9.7.4.2 Design of Working Mode of Infrared Channel

The working modes of the infrared channel can be divided into imaging, calibration, focusing, and waiting for imaging mode. In the imaging mode, continuous imaging is carried out in single-band with a fixed frame frequency of 1 Hz; in the calibration mode, the blackbody is successively switched and imaged at room temperature and high temperature according to the calibration instruction, and the initial position of the blackbody is restored after calibration; in the focusing mode, the adjustment of focal plane position is realized according to the focusing power-up instruction and the setting instruction of focusing parameters; in the waiting for imaging mode, the infrared channel is waiting for imaging instruction during the nonimaging period on-orbit.

9.7.5 Design of Camera Optical Machine System

The imaging in the visible light band and the infrared band share the RC dual-reflection primary optical system. Light in the visible light band enters the correction mirror group through the surface reflection of the color splitter, and the spectral switching is realized through the filter. Light in the infrared band transmits through the color splitter and enters the secondary imaging correction mirror group. The switching between the main and backup optical path can be realized through the switching mirror. The configuration diagram is shown in Fig. 9.5.

The function of the camera main body is to acquire the spectral energy of reflection and radiation from the observation target through optical lens, and convert the optical signal into an electrical signal through the detector. After digitization and coding, an electrical signal is transmitted to the satellite data transmission system. Optical-mechanical structure of high-resolution imager is used to integrate components of a high-resolution imager and realize high-precision installation on satellite platform. The main body of the camera is connected with the satellite integrated structure through a damper truss. The main optical axis of the camera is in consistency with the central axis of the bearing cylinder of the satellite platform. The star sensor is mounted on the side of the front bearing frame of the high-resolution imager. The satellite TT&C antenna and the star sensor heat dissipation surface are mounted on the lens hood.

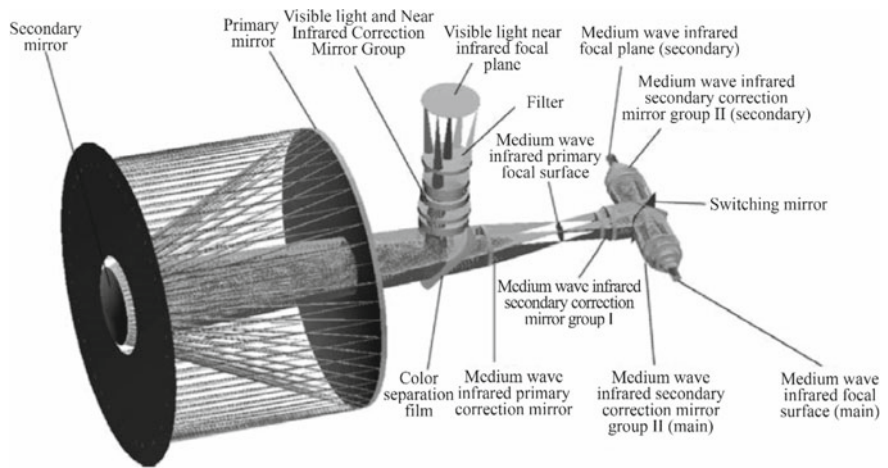


Fig. 9.5 Configuration of GEO high-resolution imager optical system, reprinted from Ref. [1], copyright 2016, with permission from spacecraft recovery and remote sensing

9.7.6 Design of Camera Electronic System

In addition to the camera main body, the subsystem has 4 independent devices, namely, visible light near-infrared management controller, medium-wave near-infrared management controller, medium-wave infrared cooling controller, and temperature controller, as shown in Fig. 9.6.

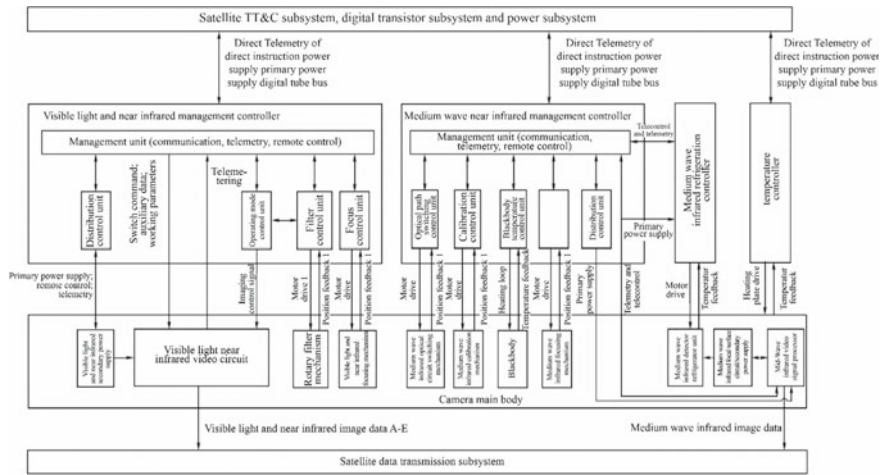


Fig. 9.6 Relationship of electronic equipment of GEO high-resolution imager

9.7.7 Design of Onboard Calibration System

The infrared channel is equipped with an onboard calibration device, whose function is to correct the nonuniformity of the infrared channel response and monitor the response of the infrared channel.

In order to ensure that the relative calibration accuracy is better than 3%, it is necessary to design a blackbody with good uniformity and variable temperature, as well as a switching mechanism for switching between blackbody at normal temperature and high temperature.

9.8 Design and Analysis of Dynamic Satellite Imaging Quality On-Orbit

On-orbit satellite imaging quality is affected by both the static optical performance and the on-orbit imaging characteristics of the camera. Firstly, the static optical performance of the camera includes radiation and geometric imaging performance, in which evaluation items for the radiation imaging quality include static Modulation Transmission Function (MTF), Signal-To-Noise Ratio (SNR), dynamic range, and radiation correction accuracy; and criteria for the geometric imaging quality include geometric distortion, registration accuracy, and positioning accuracy. Secondly, the on-orbit imaging quality of satellite is related to the static optical performance of the camera, but that is not invariable. The on-orbit imaging characteristics of satellite, important factors affecting the image quality, are affected by change of gravity and thermal environment, flutter, and transformation of reference coordinate.

9.8.1 Analysis of the Influence of Satellite Body Flutter on Imaging Quality

GEO optical satellites use an area array imaging system to gaze at Earth. Because of the high observation orbit and weak imaging energy, the imaging exposure time of GEO optical satellites is tens of milliseconds, which is much longer than that of LEO satellite push-broom imaging, so the requirement for satellite body flutter is more stringent.

Satellite flutter is caused by moving parts on it, such as camera internal refrigerator, momentum wheel, and solar wing drive mechanism, which can cause slight changes in the optical orientation of the camera during imaging. Flutter is generated by vibration sources with different frequencies and amplitudes, which results in different responses on devices at different locations due to different satellite body structures and transmission paths.

The effect of flutter on the on-orbit imaging of optical satellites is mainly reflected in the image blurring and the micro-displacement between images in time-sharing imaging in different spectral ranges. The former appears as image quality degradation, while the latter is regarded as the resource of multispectral image registration error. Because the GEO optical remote sensing system generally uses area array detectors, the relative geometric position between pixels, especially between rows or between columns, is fixed, and the interior orientation element has high stability in a short time, so the multispectral image registration can be well solved by the ground image registration processing.

High- and low-frequency flutter on the satellite will cause MTF of the camera to be decreased. Generally, the frequency $1/T_i$ corresponding to the exposure time of the camera T_i is used as the demarcation between high and low frequency.

9.8.1.1 Analysis of Requirements on Low-Frequency Flutter Suppression

Low-frequency flutter can cause aliasing when a single pixel acquires the energy of the target scene in a complete sampling process (for area array imaging, that is, an exposure time), resulting in the decrease of MTF. The MTF value of the low-frequency flutter is related to the attitude stability of the satellite in the imaging process. Such flutter is mostly caused by the physical processes such as solar wing vibration and tank liquid sloshing. The calculating formulas for MTF decline over exposure time are as follows:

$$\text{MTF}_{\text{low frequency flutter}} = \text{sinc}(\Delta d \cdot \nu) = \text{sinc}\left(\frac{\Delta d}{2d}\right), \quad (9.3)$$

where Δd is the image shift in the exposure time, ν is the Nyquist frequency, $\Delta d/d$ is the relative image shift in the exposure time.

In the process of an exposure imaging, the pixel offset should not exceed 1/3 of the pixel, and its effect on the MTF is 0.956. According to this requirement, it is actually required that over exposure time:

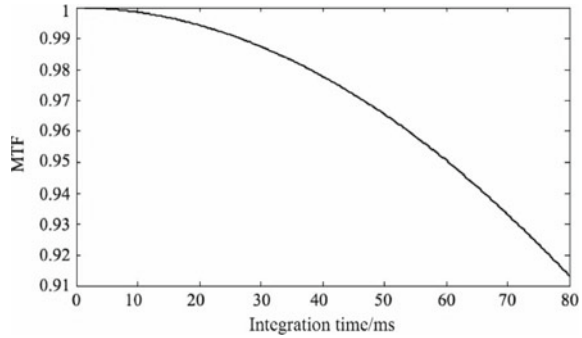
$$\omega \cdot T_{\text{int}} \leq \frac{1}{3} \cdot \frac{d}{f} = \frac{1}{3} \cdot \text{IFOV}, \quad (9.4)$$

where ω is the satellite body stability, T_{int} is the exposure time, IFOV is the instantaneous FOV, d is the pixel size, and f is the camera focal length.

Assuming the satellite stability is $5\text{E}-4^\circ/\text{s}$. Under the condition that the pixel offset is less than 1/3 pixel, the upper limit of the exposure time that the camera can achieve is 52 ms, and the corresponding frequency of 19.2 Hz is regarded as the boundary of high frequency and low-frequency boundary.

Below this frequency, the camera's boresight pointing change caused by flutter is approximately linear over the pixel exposure time, which causes the image to blur.

Fig. 9.7 Effect of continuous exposure time on MTF



By calculation, for a CMOS device with an electronic shutter, if the integration time is set from 0.1 to 80 ms and the platform attitude angular velocity is assumed as $5E-4^\circ/s$, then the MTF curve as a function of exposure time is shown in Fig. 9.7.

Therefore, it is necessary to reasonably control the MTF drop caused by the stability according to the results of the on-orbit dynamic MTF estimation, that is, to appropriately set the exposure time.

9.8.1.2 Demand Analysis of High-Frequency Flutter Suppression

Compared with LEO remote sensing satellite, GEO optical satellite has longer exposure time and wider frequency range of high-frequency flutter, which includes the characteristic frequencies of motion equipment on satellite platforms such as camera internal refrigerator, momentum wheel, and SADA.

High-frequency flutter will cause optical axis jitter during sampling, which can lead to MTF decline, so the vibration amplitude of high-frequency flutter should be controlled. According to the common sampling theory, the exponential function method is suitable for high-frequency random vibration. The MTF descent formula is as follows:

$$MTF_{\text{high frequency flutter}} = \exp[-2\pi^2 \cdot (\Delta d \cdot v)^2] = \exp\left[-\frac{1}{2}\pi^2 \cdot \left(\frac{\Delta d}{d}\right)^2\right], \quad (9.5)$$

Under the higher frequency, flutter can continue for more than one complete circle over an exposure time of the camera, so the angular displacement of the camera optical axis can be estimated according to the maximum flutter amplitude. If the flutter angular displacement of the camera optical axis corresponds to the size of 0.1 pixels on the image plane, the corresponding MTF will be decreased to 0.952. In this range, it is considered that it has little effect on the image quality. According to this requirement, it is required over the exposure time that

$$D \leq \frac{1}{10} \cdot \frac{d}{f} = \frac{1}{10} \cdot \text{IFOV}, \quad (9.6)$$

where D is the amplitude of flutter with high frequency.

Therefore, it is required that the high-frequency jitter of the camera optical axis caused by high-frequency flutter on the satellite should be less than $0.1364 \mu\text{rad}$, i.e., $0.028''$ (within 52 ms, P - P value) at frequencies above 19.2 Hz.

9.8.1.3 Design Guarantee of the Effect of Micro-Vibration on Imaging Quality

The influence of micro-vibration on imaging is very crucial, so it is necessary to deeply analyze the characteristics of the disturbance source which may disturb the imaging process on the satellite. For onboard disturbance sources, 0.1 Nm momentum wheel, 0.5 Nm momentum wheel, refrigerator, and solar wing drive mechanism are considered. In order to study the influence of various kinds of vibration, the vibration characteristics of these main moving parts are tested firstly. Secondly, the power spectrum characteristics of various vibration sources, the transmission path characteristics of vibration, the response characteristics of main imaging components, and the influence characteristics of each component on imaging are analyzed through simulation experiments.

9.8.2 Analysis of On-Orbit MTF of Satellite

The higher the MTF, the better the image contrast and edge sharpness, which is easier for human eyes to interpret. MTF is affected by target, environment, satellite, and ground processing.

Dynamic MTF of on-orbit satellite imaging can be expressed by MTF product of each part of the imaging system, as shown below:

$$\text{MTF}_s = \prod_{i=1}^n \text{MTF}_i \quad (9.7)$$

MTF of on-orbit satellite imaging can be approximately described as the product of MTF of each part. The overall response of the system is the product of MTF corresponding to each part, and evaluated by MTF at Nyquist frequency. Since the GEO optical remote sensing system uses ground gaze imaging, the system MTF in flight direction is the same as it is vertical to the flight direction. The total MTF of the system is

$$\text{MTF}_{\text{total}}(\nu) = \text{MTF}_{\text{atmosphere}} \times \text{MTF}_{\text{camera static}}(\nu) \times \text{MTF}_{\text{on-orbit environment}} \quad (9.8)$$

$$MTF_{\text{camera static}} = MTF_{\text{optical system}}(\nu) \times MTF_{\text{detecting focal plane}} \times MTF_{\text{electronic system}} \quad (9.9)$$

$$MTF_{\text{on-orbit environment}} = MTF_{\text{thermodynamics}} \times MTF_{\text{focal plane adjustment}} \times MTF_{\text{straylight}} \times MTF_{\text{vibration}}, \quad (9.10)$$

9.8.2.1 Analysis of the Influence of Atmospheric Transmission on MTF

The influence of the atmosphere on on-orbit satellite imaging is mainly represented by the MTF of atmosphere. It is generally considered that MTF is the ratio of the ground target modulation at the camera entrance pupil to the actual ground target modulation.

Among many influencing factors, satellite altitude angle has the greatest influence on scattering and absorption MTF. This is because the transfer distance of the reflected or radiated energy of the ground object to the satellite through the atmosphere varies with the direction of the satellite's line of sight (i.e., the atmospheric transmission path), as shown in Fig. 9.8.

Under the typical atmospheric conditions, the $MTF_{\text{scattering\&absorption}}$ is calculated by using the atmospheric transport model. The results are shown in Table 9.11.

The enhancement of scattering effect caused by the longer atmospheric transmission path is not only related to the path, but also to the spectral bands. For example, atmospheric molecular scattering has a greater influence on shorter spectral segments such as blue light, but less on near-infrared spectral segments with a longer wavelength. The strong backscattering in the shortwave band will result in the relatively

Fig. 9.8 Changes in atmospheric transmission paths during side-view imaging

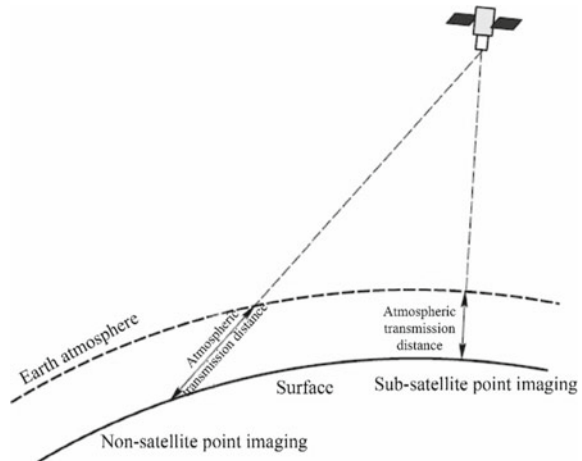


Table 9.11 Atmospheric scattering and absorption MTF at different side swing angles (0.45–0.90 μm)

The difference in longitude or latitude from the sub-satellite point/(°)	Satellite side swing angle/(°)	Satellite altitude angle/(°)	The ratio of the atmospheric transmission path of the actual imaging point to the sub-satellite point	Atmospheric scattering absorption MTF
0	0.00	90.00	1.00	0.800
20	3.45	66.55	1.09	0.761
40	6.27	43.73	1.43	0.703
60	8.06	21.94	2.56	0.607
80	8.69	1.31	9.67	0.343

small amount of radiation reflected by the ground objects in the image, and then the actual SNR of the image will be reduced.

Especially when the optical axis of the camera is pointed in the same direction as the incident light of the sun, the backscattering caused by the atmosphere is particularly strong. Middle and high latitudes are susceptible to atmospheric backscattering. For the northern hemisphere, most of them occur before the spring equinox and after the autumn equinox. According to this phenomenon, it is necessary to consider the effect of strong scattering caused by sunlight on imaging when the optical axis of the satellite is parallel to the sunlight, and to calibrate the atmospheric radiation pertinently.

9.8.2.2 Analysis of Static MTF of the Camera System

Static MTF of the Camera system is a direct measure of the modulation transfer ability of camera photoelectric imaging system for target signals with specific spatial frequencies. For the camera system, MTF at Nyquist frequency (1/2 of the spatial sampling frequency of focal plane device) of its photoelectric imaging system shall be generally concerned, whose value is mainly determined by three factors: optical system, focal plane detector, and electronic system. In addition, the static system MTF of high-resolution imager is

$$MTF_{camera\ static} = MTF_{optical\ system} \times MTF_{detecting\ focal\ plane} \times MTF_{electronic\ system} \cdot \tag{9.11}$$

(1) MTF of the optical system

Taking the design of high-resolution imager for satellite GF-4 as an example, the design parameters of optical system are as follows:

Table 9.12 Average MTF value of multispectral camera in each spectrum band

Band	B1	B2	B3	B4	B5	B6
MTF	0.311	0.365	0.336	0.323	0.290	0.360

- (1) Focus length: 6600 ± 33 mm for the visible light channel, 1350 ± 7 mm for mid-wave infrared channel;
- (2) FOV: not less than $0.8^\circ \times 0.8^\circ$ for the visible light channel, not less than $0.66^\circ \times 0.66^\circ$ for medium-wave infrared channel;
- (3) Transmittance: not less than 0.4 for each band of the visible channel, and not less than 0.5 for the mid-wave infrared channel;
- (4) Stray light coefficient: less than 3% for both visible light and mid-wave infrared channels.

According to the design results of the optical system, taking the processing adjustment factor (the value of each band is set as 0.85) into account, the average MTF of high-resolution imager in each band is shown in Table 9.12.

(2) MTF of focal plane detector

According to the test data of CMOS detector and infrared device, the design value of MTF in each band is more than 0.5.

(3) Imaging electronic system MTF of camera

The image signal of high-resolution imager is affected by various noises. In order to ensure the SNR, the bandwidth of the amplifier must be limited, and the MTF will decrease to a certain extent. The MTF influence factor of the general imaging circuit is about 0.98.

In summary, the static MTF of each spectrum segment of the high-resolution imager is shown in Table 9.13.

9.8.2.3 Effect of On-Orbit Satellite Stray Light on MTF

Compared with the point light source signal used in the camera MTF measurement on ground, which is different from the light source of the ground targets in on-orbit imaging process, the light outside FOV has a certain influence on MTF. According to the design requirements, the stray light should not be greater than $G = 3\%$ and the apparent MTF descent factor is 0.97 for the high-resolution imager with design to eliminate the stray light.

Table 9.13 Estimation of static MTF of high-resolution imager for each spectrum band

Items		Spectral range/ μm	MTF
Optical system		0.45–0.90	0.311
		0.45–0.52	0.365
		0.52–0.60	0.336
		0.63–0.69	0.323
		0.76–0.90	0.290
		3.50–4.10	0.360
CMOS detecting focal plane		0.45–0.90	0.50
		0.45–0.52	0.50
		0.52–0.60	0.50
		0.63–0.69	0.50
		0.76–0.90	0.50
Medium-wave device		3.50–4.10	0.50
Imaging circuit		–	0.98
Static MTF of the camera	Visible light spectral band	0.45–0.90	0.152
		0.45–0.52	0.179
		0.52–0.60	0.165
		0.63–0.69	0.158
		0.76–0.90	0.142
	Mid-wave infrared spectrum	3.50–4.10	0.176

9.8.2.4 Effects of Satellite Attitude Stability and Flutter on MTF

(1) MTF decline caused by low-frequency flutter

Generally, the camera axis of sight rotates around the center of mass along with the whole satellite because of the low-frequency attitude change of the whole satellite caused by the attitude stability. During the exposure time, the image point position of the camera image will be changed due to this rotation angle, which can affect the MTF value of the image after focal plane sampling. The image shift can be calculated by the following formula:

$$\Delta d = \tan(\omega t) \cdot f,$$

(9.12)

where ω is the stability of the satellite, f is the focal length and t is the exposure time. Taking a visible CMOS focal plane with the longest exposure time of 52 ms as an example, the attitude stability of satellite is assumed as $5\text{E-}4^\circ/\text{s}$ (3σ), and the image drift as $2.6\text{E-}5^\circ$, corresponding to 0.3 pixels, then $\text{MTF}_{\text{low-frequency flutter}}$ is determined to be 0.956. For infrared spectrum, the exposure time is assumed as

20 ms, the attitude stability of satellite as $5\text{E}-4^\circ/\text{s}$ (3σ), and the phase drift caused by low-frequency flutter as 0.015 pixels, then $\text{MTF}_{\text{low-frequency flutter}}$ is determined to be 0.9999, so the decrease of MTF can be neglected.

(2) MTF decline caused by high-frequency flutter

High-frequency flutter MTF refers to a decrease of MTF caused by the relative image shift (also known as optical axis jitter) of the high-resolution imager during the exposure time, to which is led by the high-frequency flutter of the moving parts of satellites passing to the image plane of the camera. Generally, the pixel offset caused by high-frequency flutter should not exceed 1/10 pixels in one exposure imaging process, and the effect on the transfer function is 0.952 (high-frequency flutter is calculated by exponential function method).

According to this requirement and the analysis in Sect. 9.8.1, it is required that the high-frequency jitter caused by the transmission of high-frequency flutter on high-resolution imager should be less than $0.1364 \mu\text{rad}$, or $0.028''$ (within 52 ms, P -value) at the frequency above 19.2 Hz.

9.8.2.5 Influence of On-Orbit Satellite Thermodynamic Characteristics on Imaging MTF

(1) MTF decline caused by the change of on-orbit camera thermodynamic characteristics

Space thermal and mechanical environment will cause certain changes in the camera structure, which will affect the MTF of the camera optical system. According to general experience, the influence factor of space environment on the system MTF is specified as 0.97 for a certain design margin.

(2) MTF decline caused by the focal surface change

The optimal focal plane position will be changed after injection, because the camera will be affected by factors such as vacuum environment, temperature field change, and weight loss. The best image quality position can be found through on-orbit focusing. $\text{MTF}_{\text{focal plane adjustment}}$ can reach 0.98 due to the influence of adjustment error and judgment error.

9.8.2.6 On-Orbit Dynamic MTF Estimation

The on-orbit dynamic MTF estimation of GF-4 is shown in Table 9.14. It can be seen that high-frequency flutter has a great influence on the imaging quality of the system. Thus, for GEO remote sensing satellites, the suppression and verification of their high-frequency flutter characteristics is the key to the overall design of GEO remote sensing satellites.

Table 9.14 On-orbit system MTF estimation, reprinted from Ref. [2], copyright 2016, with permission from spacecraft engineering

Influence factors	Estimation of MTF influencing factor
$MTF_{\text{atmosphere (sub-satellite)}}$	0.8
MTF_{camera}	Panchromatic: 0.152; multispectral: 0.161; mid-wave: 0.176
$MTF_{\text{low-frequency flutter}}$	0.956
$MTF_{\text{high-frequency flutter}}$	0.952
$MTF_{\text{stray light}}$	0.97
$MTF_{\text{thermodynamics}}$	0.97
$MTF_{\text{focal plane adjustment}}$	0.98
$MTF_{\text{system (sub-satellite)}}$	Panchromatic: 0.102; multispectral: 0.108; mid-wave: 0.118

9.8.3 Dynamic Range Analysis of On-Orbit Satellite Imaging

Whether the dynamic range design is reasonable is directly related to the level, brightness, and contrast of satellite images, and ultimately affects the image quality. The dynamic range of on-orbit satellite imaging is mainly affected by external imaging conditions, detection focal plane characteristics, circuit characteristics, and settings of system parameters. In addition to circuit optimization design and other assurance measures in design, the dynamic range should be ensured to be suitable for different external imaging conditions mainly by reasonably setting on-orbit operating parameters, as shown in Fig. 9.9.

Fig. 9.9 Influence factors of on-orbit dynamic range

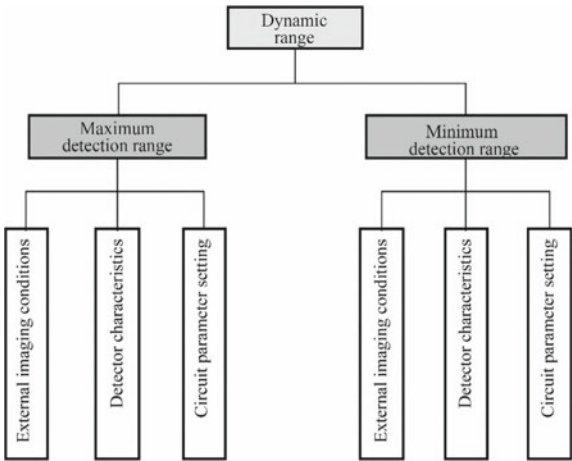
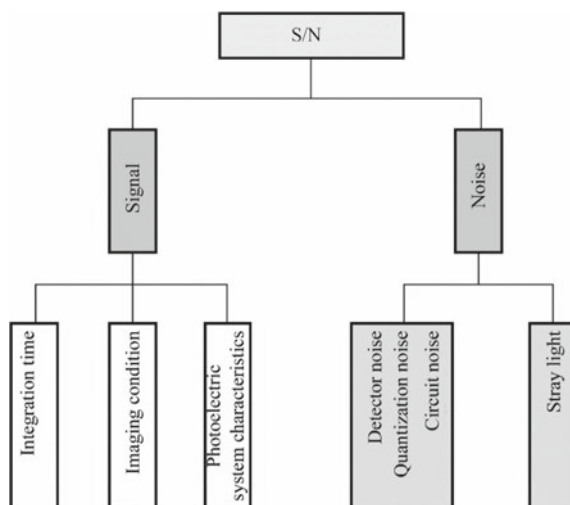


Fig. 9.10 Analysis of on-orbit SNR influence factors



9.8.4 SNR Analysis of On-Orbit Satellite Imaging

9.8.4.1 Analysis of SNR Influence Factors

SNR of on-orbit satellite imaging is mainly determined by signal power and noise power. The signal power is mainly related to the imaging conditions, such as illumination condition and target spectral reflectance, and the relative aperture, optical efficiency of the system, and the photoelectric characteristics of the system receiving elements. Noise power is mainly related to stray light control characteristics of optical systems, noise characteristics of detectors, electronic circuits, etc. A diagram is shown in Fig. 9.10.

Higher SNR can be obtained by reasonably planning exposure time in GEO optical remote sensing system. The noise generation process of the GF-4 high-resolution imager focuses on photon shot noise, dark current noise, A/D quantization noise, and random noise. Photon shot noise is the intrinsic noise of the device and its value is equal to the square root of the signal size. For the dark current noise, the dark current can be suppressed to a great extent by reducing the working temperature of the detector. In view of the above noise characteristics, the design measures are taken for high-resolution GF-4 imager, such as using high-speed and low-noise CMOS devices, focal surface thermal control, imaging electronic system design, and stray light suppression.

9.8.4.2 SNR Test and Verification

In visible light channel radiation calibration test, uniform light sources of multiple levels with different radiance outputs are provided by the integrating sphere radiation

Fig. 9.11 SNR test site
(integral sphere color
temperature about 2800 K)



calibration system. The output characteristics of the camera system under different radiance conditions are recorded by the data acquisition system. Besides, the integrating sphere radiation calibration data corresponding to different imaging parameters can be obtained by changing the exposure time of the camera system at each radiance level. Through analysis and processing, the response curve, dynamic range, SNR, pixel response consistency of the camera system, and the relationship between the output of the camera system and the combination of different parameters are obtained. See Fig. 9.11.

SNR data processing is calculated by dividing the mean value of the signal by the noise Root Mean Square (RMS). The light source and exposure time are adjusted to obtain different groups of image data. Then the image acquisition is carried out and SNR is calculated by means of calculating the mean grayscale and noise RMS of the image.

Taking the output of m rows $\times$ n columns (take $m = 1024$, $n = 1024$) of pixels as the image to be measured, the mean $\bar{S}$ of rows $m \times$ columns n of pixels is first calculated as

$$\bar{S} = \frac{\sum S_{ij}}{m \times n}, (i = 1 \dots m; j = 1 \dots n) \quad (9.13)$$

The noise value is obtained by subtracting the mean value from the signal value of each pixel:

$$\Delta S_{i,j} = S_{i,j} - \bar{S}. \quad (9.14)$$

RMS value of noise is

$$\text{Noise}_{\text{rms}} = \sqrt{\frac{\sum_{m \times n} \Delta S_{i,j}^2}{m \times n}}. \quad (9.15)$$

SNR is calculated according to the formula of SNR as follows:

Table 9.15 SNR Value of high-resolution imaging system

Spectral band	Imaging state (solar altitude angle/(°), reflectivity)	Exposure time/ms	Mean SNR of all pixels/dB
B1	80, 0.8	2.1	50.1
	10, 0.05		23.2
B2	80, 0.8	9.6	50.1
	10, 0.05		23.2
B3	80, 0.8	7.8	50.4
	10, 0.05		23.8
B4	80, 0.8	11.8	50.0
	10, 0.05		24.0
B5	80, 0.8	14.7	50.2
	10, 0.05		25.7

$$\frac{S}{N} = 20 \lg \frac{\bar{S}}{\text{Noise}_{\text{rms}}}. \quad (9.16)$$

The above is the SNR calculation method of a single image. The final SNR is the average of the calculated value of the five images.

Based on the calculated value of the equivalent entrance pupil radiance under different observation conditions, the integrating sphere radiance is adjusted according to the range of the entrance pupil radiance required by the camera test until the equivalent entrance pupil radiance of the camera reaches the radiance level in the table. Then, the SNR of each spectrum segment of the camera is obtained by calculation using the measured data, as shown in Table 9.15.

It can be found that the SNR is better than 23 dB at the low end of bands B1–B5 at the solar elevation angle of 10° and the reflectance of ground objects of 0.05, and 46 dB at the solar elevation angle of 80° and the reflectance of ground objects of 0.8.

9.8.5 Laboratory Calibration Accuracy Analysis

9.8.5.1 Analysis of Calibration Accuracy of Visible Light Spectral Band

The main factors affecting the absolute accuracy of laboratory radiation calibration in the visible light spectral band are standard transfer error, uncertainty of radiometer measurement, surface and angular uniformity of integrating sphere, stability of integrating sphere radiance, and stray light of camera. The analyzed influence factors are shown in Table 9.16.

The main factors affecting the relative accuracy of laboratory radiometric calibration of the visible light spectral band are the error of surface and angular uniformity

Table 9.16 Analysis of absolute calibration accuracy of visible light spectral band

Influencing factors	Absolute calibration error/%	Relative calibration error/%
Standard transfer error	5	—
Uncertainty of radiometer measurement	2	—
Integral spherical uniformity error	1.5	
Integral spherical angle uniformity error	1	
Integral sphere radiance stability error	0.5	
Camera stray light	2.5	—
Total error	6.2	1.9

of integrating sphere and the stability of integrating sphere radiance. Through calculation and analysis, the influence amount of each influencing factor is shown in Table 9.16.

9.8.5.2 Analysis of Calibration Accuracy of Mid-Wave Infrared Spectral Band

For the calibration of the infrared channel of the camera, black body radiation is collimated and expanded by the collimator and then enters the camera entrance pupil. From the perspective of energy transmission in vacuum radiation calibration, the main factors affecting the absolute calibration accuracy of infrared channel in laboratory are blackbody radiation source, cryogenic collimator, and infrared detector. After analysis, the influence factors are shown in Table 9.17. The main factors affecting the relative calibration accuracy of infrared channels are surface uniformity and stability of blackbody radiation and stability of the output signal.

9.8.5.3 Onboard Relative Calibration Accuracy of the Mid-Wave Infrared Channel

With the onboard calibration device of the infrared channel, the relative calibration is performed full-aperture half-optical path on the infrared image, and correction data for nonuniformity correction of the image is provided. The onboard relative calibration accuracy is mainly affected by the relative calibration accuracy of the

Table 9.17 Absolute/relative calibration accuracy analysis of infrared channel

Absolute calibration accuracy analysis		Relative calibration accuracy analysis	
Influencing factor	Influence percentage/%	Influencing factor	Influence percentage %
Measurement error of blackbody temperature	3.7	Surface uniformity error of blackbody radiation	1.2
Reflection efficiency error of collimator	0.5	Illumination stability error of Blackbody radiance	1.2
Output signal stability error	0.4	Camera output signal stability error	0.4
Total error	3.8	Total error	1.74

onboard calibration before the camera is launched and the stability of the performance of the calibration device.

After the injection, the emissivity and temperature control accuracy of the onboard blackbody radiation source may be changed, resulting in poor stability. Irregular monitoring and calibration can be carried out by using ground radiation correction field, and the calibration accuracy is expected to be within 2%.

Based on the analysis of the main factors affecting the radiation calibration accuracy on-board, it is estimated that the onboard calibration accuracy of infrared channel can be controlled within 2.65%.

9.8.6 Geometric Positioning Accuracy Analysis

The factors affecting the geometric quality of GF-4 satellite images are mainly characterized by parameters such as positioning accuracy, registration accuracy, and geometric distortion. Image positioning accuracy refers to the deviation between the coordinate position of a reference target measured by the remote sensing image and its actual position.

The main factors affecting the accuracy of geometric positioning on satellite are satellite attitude measurement accuracy, satellite orbit determination accuracy, and satellite time synchronization accuracy. These factors include system error, low-frequency error, and random error. System error can be corrected by geometric correction in ground positioning processing, and RMS error of geometric positioning accuracy is mainly caused by random error and low-frequency error of each influencing factor. The influencing factors of geometric positioning accuracy are shown in Table 9.18. The system error in the table can be improved by on-orbit system calibration, but not the random error. Measures must be taken during the design process to reduce the error as much as possible in order to ensure that the positioning accuracy indicator finally meets the requirements. Based on the analysis of the factors

Table 9.18 Influencing factors and error analysis of geometric positioning accuracy, reprinted from Ref. [2], copyright 2016, with permission from spacecraft engineering

Influencing factor	Influencing factor item decomposition	Error characteristic	Control precision	Pre-calibration error	Post-calibration error
Time	Onboard time synchronization accuracy/ms	Random	0.05	0	0
Orbital measurement	Orbital accuracy/m		200	30.1	30.1
	Ground loading error	System	10	1745.3	0
	Star sensor and camera measurement accuracy/($''$)				
	Camera cubic mirror lead error/($''$)		10	1745.3	0
	Star sensor cubic mirror lead error/($''$)		10	1745.3	0
Attitude measurement error	On-orbital environment change	Low frequency	0.1 pixel	5	523.6 m
	Camera distortion stability		20	3490.7	
	On-orbit thermal deformation (stability of the angle between star sensor and camera)/($''$)				
	On-orbit residual stress deformation/($''$)	System	20	3490.7	0
	Star sensor measurement accuracy/($''$)	Random	3	523.6	523.6
	Star sensor and orbit calculation time synchronization error/($''$)	Low frequency random	7	1221.7	1221.7
			0.15	26.2	0.15/26.2

(continued)

Table 9.18 (continued)

Influencing factor	Influencing factor item decomposition	Error characteristic	Control precision	Pre-calibration error	Post-calibration error
Stable attitude	Attitude stability/[$(^{\circ}) \cdot s^{-1}$]		5×10^{-4}	78.5	78.5
Location algorithm	Ground calibration residual error		3 pixels	150	150
Comprehensive positioning accuracy				8403.0	2035.3

affecting the positioning accuracy, the positioning accuracy of GF-4 is controlled, as shown in Table 9.18.

9.9 On-Orbit Calibration Analysis of High-Orbit Optical Remote Sensing System

After the injection, the radiation and geometry must be calibrated on-orbit. Based on the characteristics of GF-4, a set of cross-calibration method is adopted in the ground processing system to realize the radiometric and geometric calibration.

9.9.1 On-Orbit Relative Radiation Calibration

Based on the image data acquired synchronously by GF-1 and the GF-4, and taking the geometric model of the 16 m WFV camera of the GF-1 as a reference, the calibration model of the interior and exterior azimuth elements at the synchronous transit moment of the GF-4 is established. Then, the strict geometric model of the moment is used as a reference to establish the geometric relationship of the GF-1 and the GF-4, the imaging simulation and calibration of GF-4 on its focal plane are realized. The flowchart is shown in Fig. 9.12.

9.9.2 On-Orbit Absolute Radiation Calibration

9.9.2.1 Absolute Radiation Calibration for Visible Light Bands

When the high-resolution imager is used to image the radiation correction field, the ground equipment simultaneously measures the surface reflectance, atmospheric optical parameters, and other parameters. Combining with the atmospheric radiation transfer model, the radiance on the pupil of the satellite is calculated, and then the equivalent radiance is obtained by convoluting the radiance with the spectral response function of the high-resolution imager. Finally, the calibration coefficient is calculated by comparing the equivalent radiance value with the actual observation value of the satellite. The implementation process is shown in Fig. 9.13.

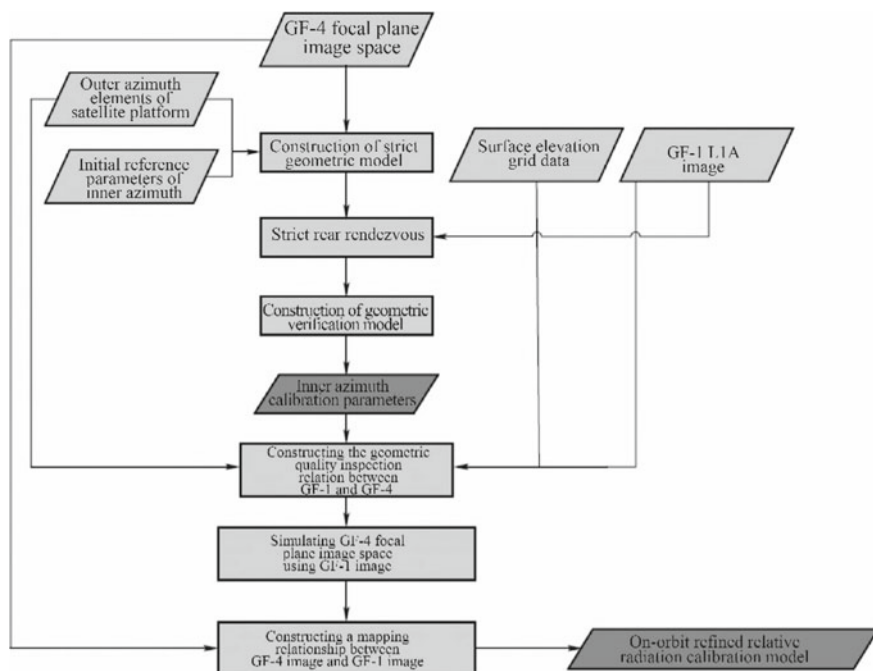


Fig. 9.12 On-orbit calibration process of relative radiation of satellite GF-4, reprinted from Ref. [3], copyright 2016, with permission from spacecraft recovery and remote sensing

9.9.2.2 Absolute Radiation Calibration in Medium-Wave Infrared Band

The relationship between the images of target remote sensor and reference remote sensor is established by using cross-calibration method and taking the calibration precision remote sensor as reference. Then, the apparent radiance of the target remote sensor image is calculated with the calibration coefficient of reference remote sensor. Combined with the image digital value of site, the calibration coefficient of remote sensor is obtained. The implementation process is shown in Fig. 9.14.

9.9.3 On-Orbit Geometric Calibration of Two-Dimensional Array Payloads

Due to the complex high-orbit environment and special imaging mode, different from the traditional linear CCD of the push-broom type satellite, the geometry model of satellite GF-4 requires the construction of strict geometric imaging model and calibration model specific to the array sensor. Firstly, appropriate single-view data

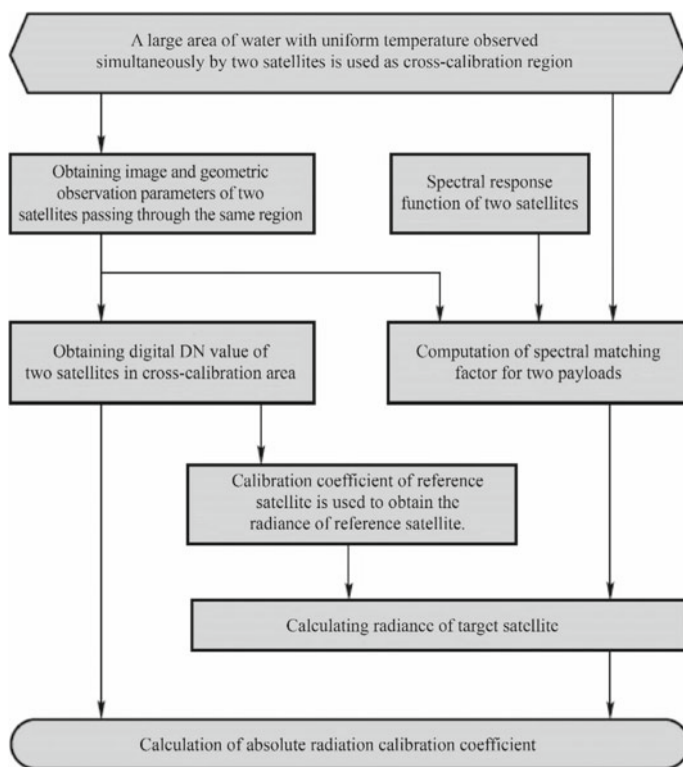


Fig. 9.14 Absolute radiation calibration process in the infrared band

9.10 Application of High-Orbit Optical Remote Sensing Satellite

The satellite GF-4 under good on-orbit condition was successfully launched on December 29, 2015. GF-4 meets the quality requirements of remote sensing data such as vegetation, water body, snow cover, cloud system, large landslide, barrier lake, forest land, wetland, forest fire point and plays an important role in disaster reduction, meteorology, earthquake, forestry, environmental protection, and other industries.

9.10.1 Fast Mission Response Application

The satellite GF-4 is operating on geostationary orbit without limitation of the transit time. Taking advantage of its long-term presence in the fixed area, GF-4 detects and

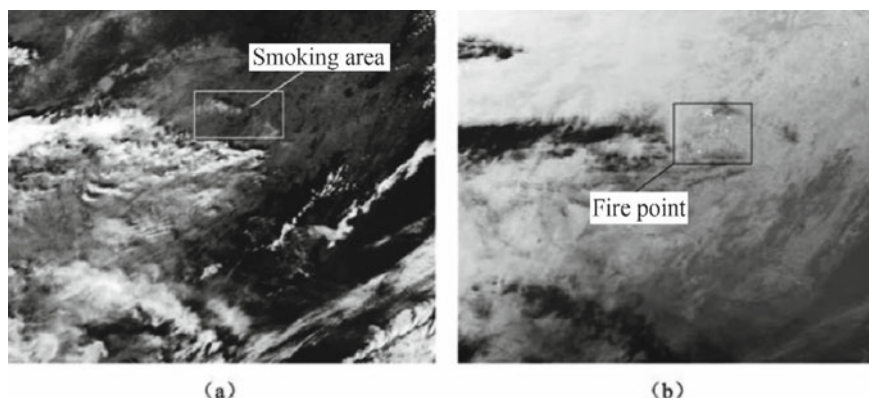


Fig. 9.15 Australian forest fire images photographed by GF-4 on January 2, 2016, reprinted from Ref. [4], copyright 2016, with permission from Spacecraft Engineering. **a** Panchromatic multispectral band. **b** Mid-wave infrared band

monitors the interest target in real time with its high maneuver ability according to the observation task.

For applications such as fire monitoring, GF-4 can distribute the image data to users within 15 min after requests with its fast mission response capability. Figure 9.15 shows the Australian forest fires images taken by the GF-4 satellite.

9.10.2 Application of Continuous Target Observation

Taking advantage of being stationary relative to the ground and high-time resolution, the satellite GF-4 can perform high-frequency repeated gaze observations on the target area over a period of time and obtain dynamic change course data of the target area. In the actual observation of the typhoon, GF-4 can not only continuously provide typhoon development and change information, but also use the higher spatial resolution to distinguish the cloud texture information of typhoon in detail, thus providing remote sensing data for the relevant departments to predict typhoon development trends. Figures 9.16 and 9.17 show the image of Super Typhoon Nepartak taken at high frequency by the GF-4 satellite.

9.10.3 Application of Large-Scale Situation Awareness

Large-swath and high-time-resolution data have shown its advantages in meteorological environmental monitoring, especially for the rapid weather changes in some key areas and the analysis of air pollution hazards. Large-swath and high-time-resolution

Fig. 9.16 Central image (panorama) of Super Typhoon Nepartak taken by GF-4 on July 7, 2016

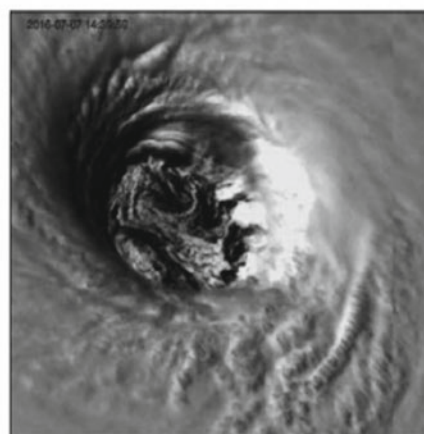
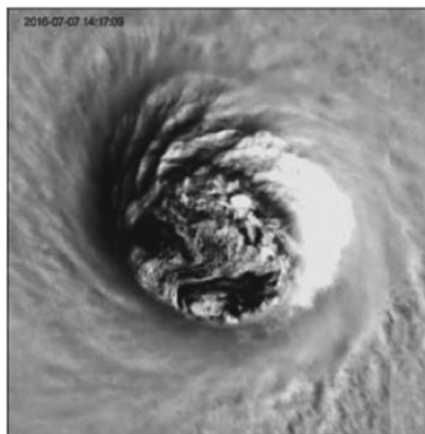
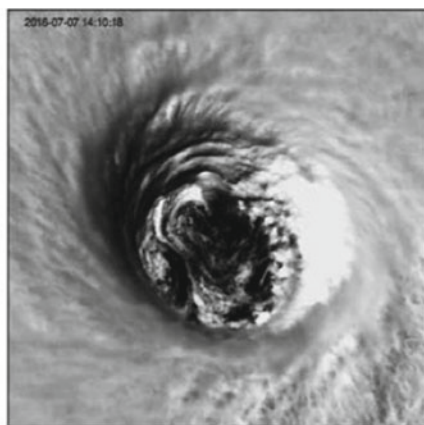
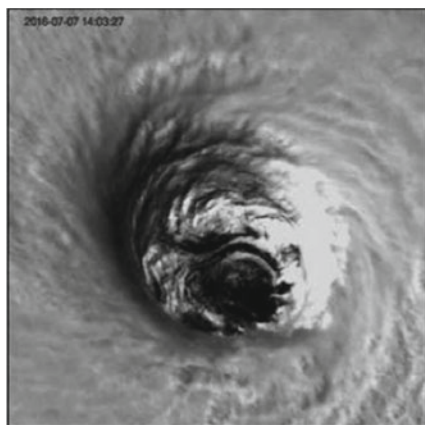
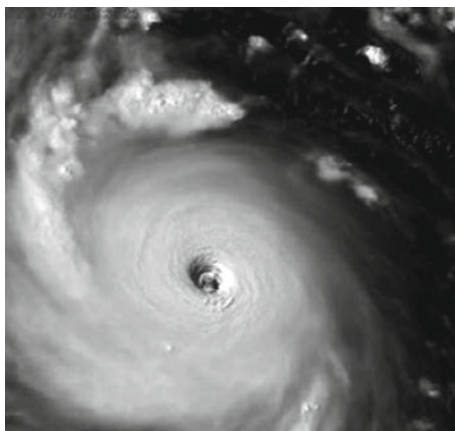


Fig. 9.17 Central images (local) of super typhoon Nepartak taken by GF-4 on July 7, 2016

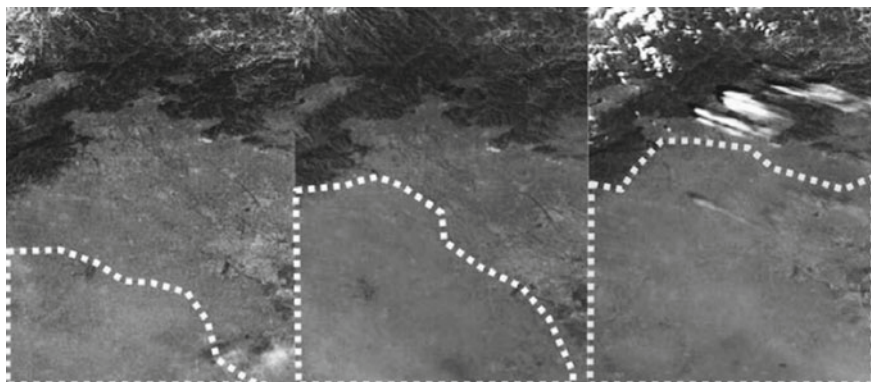


Fig. 9.18 The haze-derived development image taken by GF-4 satellite in Beijing–Tianjin–Hebei region, reprinted from Ref. [4], copyright 2016, with permission from spacecraft engineering

data also have strong pertinence and the character of real time for the early warning of atmospheric hazards in adjacent areas. Figure 9.18 shows a derivative image of haze change taken by GF-4 in Beijing–Tianjin–Hebei region.

9.11 Summary

If the camera on the geostationary orbit is expected to achieve a resolution better than 5 m, its optical system should have an aperture size of 3–4 m. However, due to the limitation of many factors, such as the manufacturing and processing of mirror blanks, the on-orbit quality maintenance of mirror surface, etc., the traditional integral primary mirror technology can hardly meet the task requirements when the aperture size of the optical system is larger than 4 m. In addition, limited by the capability of the launch system, the maximum aperture size of the optical system can only be up to 4 m.

Hence, in order to develop an Earth observation system with a resolution better than 5 m on geostationary orbit, it is necessary to seek a technical approach other than the traditional integral primary mirror. To this end, the United States, Europe, and other countries (regions) are developing new imaging technologies, such as the deployable segmented mirror imaging technology represented by the “James Weber Space Telescope (JWST)”, thinfilm diffraction imaging technology represented by the “MOIRE” program, and the optical synthetic aperture imaging technology represented by the adaptive reconnaissance ARGOS satellite project, and other new imaging technologies that can achieve higher resolution than traditional imaging systems.

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Chapter 10

Development Prospect



The future development trend of satellite remote sensing technology is closely related to the needs of various industries and fields, mainly reflected in the following aspects: the first is the satellite remote sensing technology system closely related to the “Internet +;” the second is to construct a remote sensing satellite system by fully utilizing the characteristics of remote sensing satellites with different orbit types; and the third is the new remote sensing technologies to be developed in the future.

10.1 Future New “Internet + Satellite Remote Sensing + Big Data + Digital Earth” System

As a strategic resource with great application value, the satellite remote sensing data will be deeply integrated in the emerging strategic industries such as mobile internet, global navigation, Internet of Things, cloud computing, big data analysis, and serving all aspects of human society. The remote sensing data have the characteristics of global, multi-view, multi-dimension, and multi-scale. With the development of technology and industry, global data resources obtained from remote sensing satellites, such as climate, ecology, and environmental change data, have increasingly important application values, and will also become indispensable basic data for high-precision digital Earth, smart Earth, smart city, and smart transportation in the future.

As shown in Fig. 10.1, satellite remote sensing characterized by multi-detection means, multi-resolution, multispectral, multi-dimensional, all-day, and all-weather plays an increasingly important role in the construction of smart city, national census,

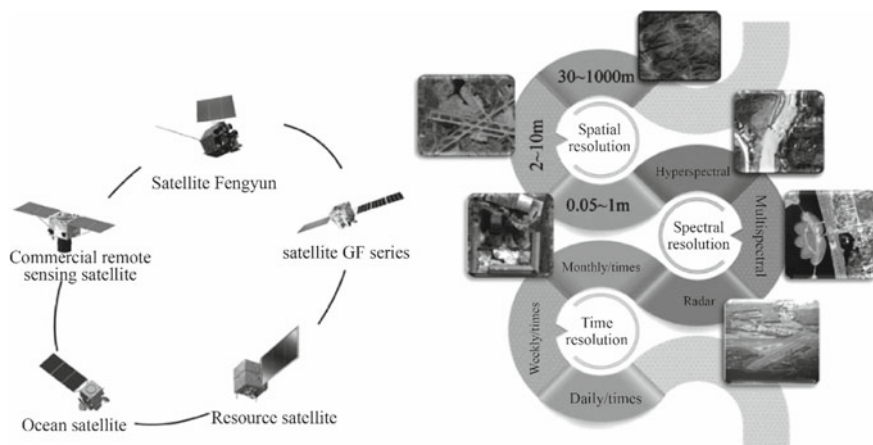


Fig. 10.1 Multiple remote sensing data sources based on satellite remote sensing data

environmental improvement, land rights confirmation, such as improving the monitoring of land resources, ecological environment monitoring, and is gradually used in national security, ocean, transportation, new energy, and other fields.

“Internet + remote sensing” is not to overturn the remote sensing industry, but to enhance it. “Internet + satellite remote sensing” spawned remote sensing cloud services, and improved the real-time performance of satellite remote sensing services, as shown in Fig. 10.2. Internet companies will increasingly use space-based remote sensing data services to promote the upgrading of existing business, to accelerate the integration of aerospace technology and application industry into the information service industry, and to achieve great development in large industries, as shown in Fig. 10.3.

10.2 High-Resolution Earth Observation Satellite System Combining LEO, MEO, and HEO

Aerospace powers such as the United States and France attach great importance to the joint observation system with LEO satellite for global coverage, MEO satellite for continuous surveillance, and HEO satellite for wide area surveillance. The United States first developed a space-based high-resolution integrated reconnaissance and surveillance system consisting of KH-12 + Lacrosse satellite LEO system, 8X satellite MEO system, and HEO high-resolution optical imaging system. Among them, 8X satellite operates at an orbit of 2689×3132 km with an inclination of 63.4° and visible light resolution and SAR resolution of 1 m in all-time and all-weather. The United States has put forward a practical system, as shown in Fig. 10.4, which can achieve a high resolution of 1 m in the geostationary orbit with a FOV of 10×10 km

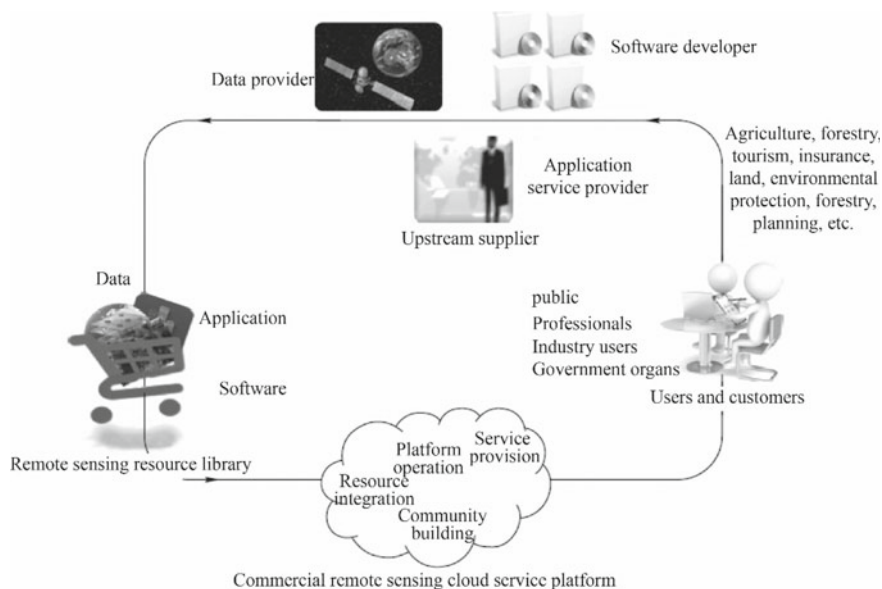


Fig. 10.2 Remote sensing cloud service platform model

and an imaging rate of up to 1 frame per second. It can realize continuous surveillance on enemy military targets, and will greatly enhance the dynamic surveillance capability of time-sensitive targets such as ships and missile launchers.

In October 2013, France proposed the development of an optical imaging satellite system combining LEO, MEO, and HEO, in which the LEO shall achieve ultra-high resolution Earth observation with the capability for daily revisit with a single satellite to any point on Earth and the optical imaging resolution range from 0.2 to 0.3 m; the MEO optical satellite operates at an inclined elliptical orbit of 6353×1261 km with inclination of 116° (the apogee is frozen in the northern hemisphere), the resolution of apogee imaging of 1 m, the swath of 50° km, and the sustained observation time of 45 min to realize the region continuous monitoring; the HEO optical satellite with the imaging resolution of 3 m can achieve the wide-area continuous monitoring with static image and dynamic video. The design status of the MEO and HEO satellites of the system is the same. At present, the geostationary orbit reconnaissance and surveillance system satellite HRGeo is proposed in Europe, and with camera caliber of 4.1 m and resolution of 3 m, as shown in Fig. 10.5.

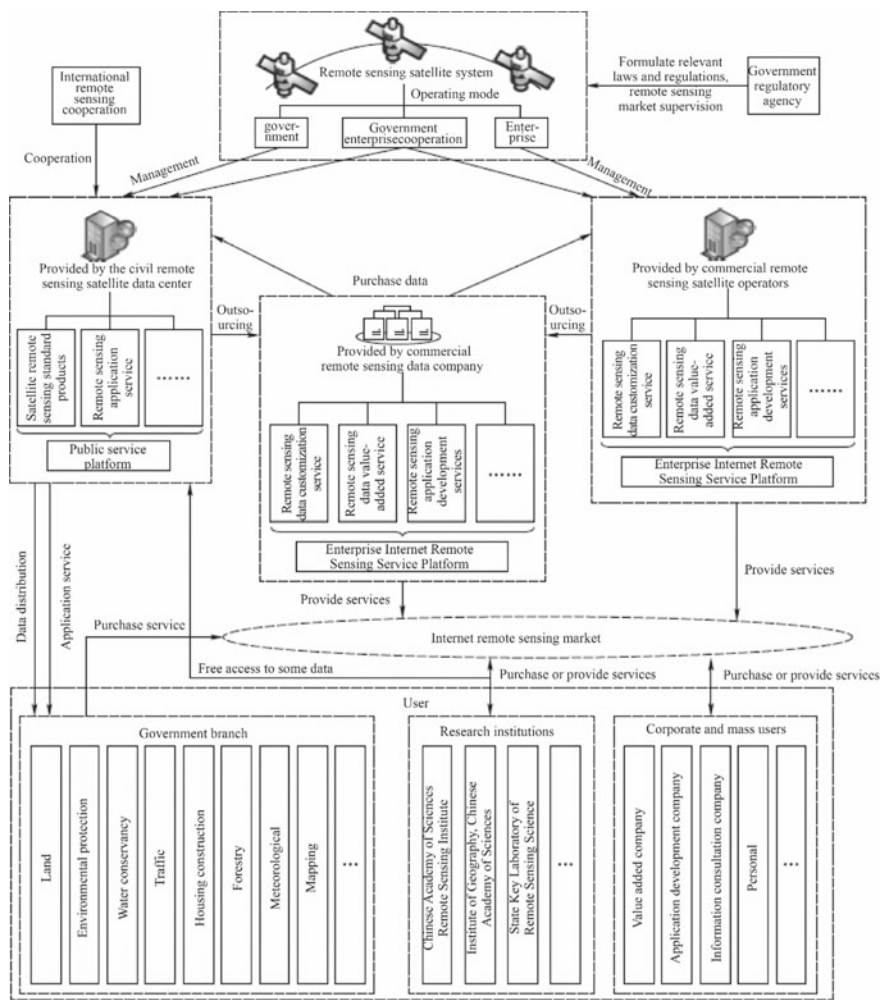
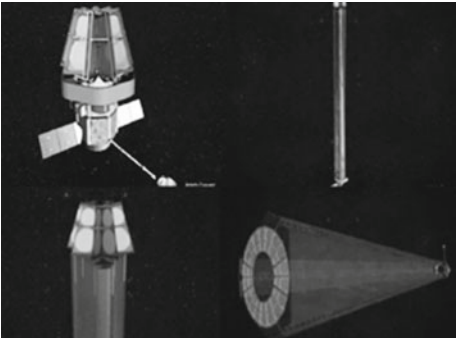


Fig. 10.3 Service architecture of “Internet + Satellite Remote Sensing + Big Data” system

Fig. 10.4 Concept of a practical geostationary diffraction imaging satellite in the United States, reprinted from Ref. [1], copyright 2014, with permission from Satellite Application



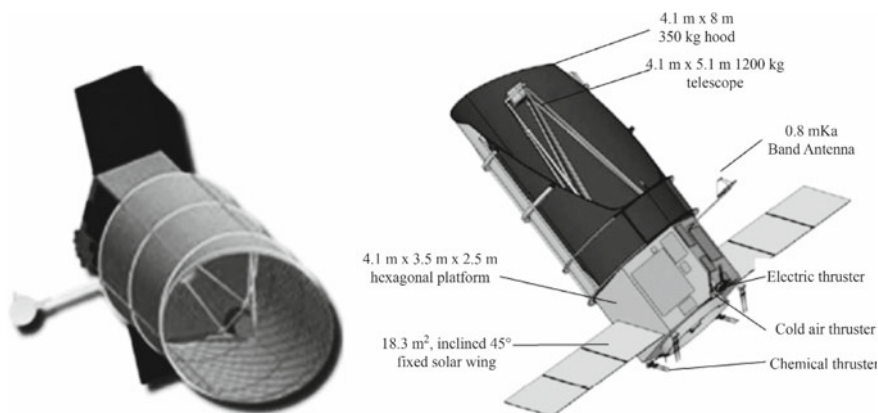


Fig. 10.5 Schematic diagram of European geostationary reconnaissance and surveillance system satellite HRGeo, reprinted from Ref. [1], copyright 2014, with permission from Satellite Application

10.3 New Remote Sensing Technology in the Future

10.3.1 *High-Resolution Satellite Remote Sensing Technology in Visible, Infrared, and Microwave Bands*

From the current global development of Earth observation satellites, the United States still maintains the leading position and begins to upgrade. The satellite KH 12 (“Key-hole Satellite”) has a visible light resolution of 0.1 m, and an infrared resolution of 0.1 m. The resolution of the future imaging system radar in satellite can reach at 0.3 m. The visible light panchromatic resolution of the American commercial remote sensing satellite WorldView-3/4 is better than 0.31 m, the multispectral resolution is 1.24 m, and the shortwave infrared multispectral resolution is 3.7 m. The visible light resolution of the French satellite Helios-2 is better than 0.25 m and the infrared resolution is 2.5 m. Russia launched the high-resolution satellite “Persona-2” in 2013, with a resolution of 0.33 m. So it can be seen that, in the near future, global satellite remote sensing applications will enter the era of high-resolution imaging integrated remote sensing applications in multispectral visible, short/medium/longwave multispectral infrared, Ka/X/C/L/S, and other broadband.

10.3.2 *High-Resolution SAR with Multi-Azimuth and -Temporal Information Acquisition Technology*

In addition to the traditional L, C, X, and S bands, the P band will also be an available space-borne microwave detection band. In the traditional SAR image, only target

scattering information in a relatively small azimuth range is reflected, which objectively makes the interpretation of SAR image difficult. In order to further improve the detection performance of radar system, space-borne SAR system based on large-angle beam scanning technology should be developed to achieve multi-directional information acquisition ability. By acquiring multi-directional radar images, the scattering and geometric characteristics of targets can be better reflected, thereby improving the interpretation ability of SAR images.

The microwave time-phase imaging technology can simultaneously acquire the dynamic change data of the target in the spatial and temporal dimensions, and is mainly used to detect the time-varying characteristics of the target. In recent years, space-borne SAR time-phase imaging technology is an important development direction, which can improve the imaging detection capability of SAR systems on medium and high orbit. The distributed SAR with high precision will become a future development direction. The United States, France, and Germany are actively trying to develop the microwave time-phase imaging technology with higher resolution, larger swath, and higher elevation accuracy by using multi-aperture and long baseline.

10.3.3 High-Sensitivity Infrared Remote Sensing Technology

With the high-temperature resolution, infrared remote sensing can be capable for many applications, such as ecological environment monitoring, air pollution monitoring, mineral exploration, geological hazard investigation, and underwater target detection and recognition. Therefore, the improvement of temperature sensitivity of infrared remote sensing is also a main development direction. The quantum well detector used by Landsat 8 (launched by the United States in 2013) can work at 40 K, and its detection sensitivity is increased to 30 mK. At present, the sensitivity of infrared detectors has reached the magnitude of 1–5 mK or lower, and the sensitivity of space infrared remote sensing will soon enter a new stage of a magnitude of mK.

10.3.4 Visible Light-Longwave Infrared Hyperspectral Imaging Technology

Hyperspectral imaging is of great significance for remote sensing on the Earth, and plays an important role in human cognition and development and utilization on the Earth. It is also the current most effective means for monitoring atmospheric, ocean, Earth, and other environmental changes, and for quantitative remote sensing inversion and application in industrial and ecological evolution. In recent years, satellite hyperspectral imaging technology has been developed rapidly. By the satellite hyperspectral imaging technology, the fine detection of spectral features of ground objects with nanometer-level spectral resolution, up to 400 spectral segments

covering the visible light, shortwave, and infrared mid-wave infrared spectrum, and the spatial resolution of 4 m has been became true.

With the rapid development of hyperspectral imaging, high-sensitivity detector, and computational spectral imaging technology, detection means will be more diverse; detection band range will be further expanded from the traditional visible light band to the ultraviolet, mid-wave and longwave infrared bands; moreover, spatial resolution and spectral resolution will be further improved so that higher quality data can be obtained.

10.3.5 Commercial Small Satellite Constellation System Promotes the Development of New Application Industry

In 2013, Planet Labs and Skybox Imaging launched their Earth Observation Satellites one after another. Both companies plan to launch super-large-scale Earth observation microsatellite constellations, which could change the global pattern of commercial satellite remote sensing industry. Skybox's first satellite, SkySat-1 launched in November 2013, also the first submicron-level array COMS imaging satellite in the world, had the capability of image correction and real-time compression, was with a mass of 91 kg and a resolution of 0.9 m, including a CMOS array sensor with a resolution of 5.5 million pixels. The global data can be updated in 8 h by the constellation system composed of 24 similar satellites. Planet Labs launched 4 technology demonstration satellites "Dove" in 2013. The mass of single satellite is only about 6 kg, with the resolution of 3–5 m. The constellation system consists of 28 nanosatellites forming the constellation "Flock-1." The satellites on orbit with an altitude of 400 km and an orbit inclination of 52° can cover the main active areas of human beings in near real time. The satellite constellation will adopt the working mode of continuous imaging facing the Earth.

These above-mentioned start-ups have successfully combined microsatellite technology with innovative business models such as cloud services, big data, customization services to realize business ideas based on low-cost, high-time, high-spatial resolution Earth image applications, and built data flow platforms related to global daily activities, thus developing new business applications.

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